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PROJECT ARMOR OBSTACLE II

Joseph Briggs

Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

April 1973

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13. ABSTRACT

Project Armor Obstacle, executed by the U. S. Army Engineer Waterways Experiment Station (USAEWES) Explosive Excavation Research Laboratory (EERL) was a series of cratering and obstacle effectiveness experiments, conducted in October and November 1972 at Fort Peck, Montana. The cratering tests consisted of several deliberate road cratering designs and a series of equal weight cratering comparisons. Explosives involved were TNT, nitromethane, a 10% aluminized slurry, ANFO, the Army's 40-lb cratering charge, and the Experimental XM-180 cratering charge. Various wheeled and tracked vehicles attempted to negotiate the road craters that were produced. Obstacle effectiveness tests were also conducted in a crater produced by 17 tons of nitromethane at 6-m depth of burial with an open access hole. Tests results demonstrated the validity of the various road crater designs and their effectiveness as obstacles. TNT and nitromethane appeared to have about the same cratering ability, and although the aluminized slurry did not perform as anticipated, it proved to have definite handling and emplacement advantages.

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PROJECT ARMOR OBSTACLE II

MAJ JOSEPH BRIGGS

Sponsored by

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Conducted by

U.S. ARMY ENGINEER WATERWAYS EXPERIMENT STATION
EXPLOSIVE EXCAVATION RESEARCH LABORATORY
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Preface

The U.S. Army Engineer Waterways Experiment Station (USAEWES) Explosive Excavation Research Laboratory (EERL) was the USAEWES Explosive Excavation Research Office (EERO) prior to 21 April 1972. Prior to 1 August 1971 the organization was known as the USAE Nuclear Cratering Group.

This is the final report on Project Armor Obstacle II. The project was conducted by EERL to study the effectiveness of explosively produced craters in stopping or impeding vehicular movement. Different explosives including a 10% aluminized slurry were used in this project. This work was funded by Office, Chief of Engineers as part of Project MEACE (Military Engineering Applications of Commercial Explosives).

The Director of USAEWES during this project was COL Ernest D. Peixotto. EERL's Director during this project was LTC Robert R. Mills, Jr. The Deputy Director (Military) was MAJ Richard H. Gates.

Abstract

Project Armor Obstacle, executed by the U.S. Army Engineer Waterways Experiment Station (USAEWES) Explosive Excavation Research Laboratory, was a series of cratering and obstacle effectiveness experiments conducted in October and November 1972 at Fort Peck, Montana. The cratering tests consisted of several deliberate road cratering designs and a series of equal weight cratering comparisons. Explosives involved were TNT, nitromethane, a 10% aluminized slurry, ANFO, the Army's 40-lb cratering charge, and the Experimental XM-180 cratering charge. Various wheeled and tracked vehicles attempted to negotiate the road craters that were produced. Obstacle effectiveness tests were also conducted in a crater produced by 17 tons of nitromethane at 6 meters depth of burial with an open access hole. Test results demonstrated the validity of the various road crater designs and their effectiveness as obstacles. TNT and nitromethane appeared to have about the same cratering ability, and although the aluminized slurry did not perform as anticipated, it proved to have definite handling and emplacement advantages.

Acknowledgments

The successful accomplishment of Project Armor Obstacle II was due to the combined efforts of many organizations and individuals. The author appreciates and gratefully acknowledges the assistance of the following:

Mr. Don Beckman, Fort Peck Area Engineer, and his staff for technical and operational support.

The Commander of the 1st Battalion, 70th Armor, 4th Infantry Division (Mechanized), Ft. Carson, Colorado, for the M-60 tank and crew.

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MAJ Roy Hovey of the U.S. Army Armor School for his advice and comments during the obstacle effectiveness test.

Mr. John Mertin, Picatinny Arsenal, for his assistance in firing the XM-180 cratering device.

Those individuals of EERL who assisted in the conduct of tests and the writing of this report.

Contents

FIGURE

FIGURE

TABLE

Conversion Factors
British to Metric Units of Measurement

British units of measurement used in this report can be converted to metric units as follows.

Multiple	By	To obtain
inches	2.54	centimeters
feet	0.3048	meters
cubic feet	0.02832	cubic meters
cubic yard	0.764555	cubic meters
pounds	0.4535924	kilograms
pounds per square inch	0.00689476	meganewtons per square meter
pounds per cubic foor	16.02	kilograms per cubic meter

PROJECT ARMOR OBSTACLE II

Chapter 1. Introduction

GENERAL

This report is a technical summary of the results of a series of cratering experiments and obstacle effectiveness tests conducted in clay shale at the Fort Peck Reservoir near Glasgow, Montana. The experimental programs consisted of several single- and row-charge detonations that ranged in charge weight from 40 to 3960 lb. The explosives used were TNT, ammonium nitrate-fuel oil (ANFO), an aluminized slurry and the Army's standard 40-lb ammonium nitrate (AN) canister. In addition to the cratering shots, several tactical vehicles that included two tanks were employed to evaluate the effectiveness of the craters as obstacles. Project Armor Obstacle II (A. O. II) was conducted by the U. S. Army Corps of Engineers Waterways Experiment Station Explosive Excavation Research Laboratory (EERL) during the period 27 October through 13 November 1972.

BACKGROUND AND OBJECTIVES

For more than 30 years, the Army's primary deliberate road cratering explosive has been the 40-lb AN canister. To supplement this cratering ability, other than with nuclear detonations, the Army prescribes the use of large quantities of TNT. From experience with these two explosives, it is apparent that the military engineer is in need of an engineering tool which will satisfy his earth moving requirements and increase his ability to rapidly defeat enemy targets in less time, with fewer men and with less equipment. The explosive industry during the past 10 years has experienced tremendous achievements in developing reliable, safe, and easy to handle explosives. These achievements, and the success EERL has had in its civil works construction program with commercial explosives,[1] have prompted the Waterways Experiment Station (WES) to initiate a research and development program on the use of commercial explosives in military applications such as barrier formation and target destruction.[2]

The objectives of Project Armor Obstacle I, which was conducted in the fall of 1971, were limited to evaluating the obstacle effectiveness of several craters produced for Project Diamond Ore IIA (D.O. IIA).[3] Project A.O. II objectives were more extensive, and were as follows:

1. To compare the cratering results of equivalent quantities of an aluminized

slurry with TNT in the same charge configuration in terms of crater dimensions and obstacle effectiveness.

2. To evaluate the handling requirements for loading and unloading both large and small quantities of slurry explosives in deep and shallow emplacement cavities.

3. To evaluate the utility of a field expedient explosive container for loading and unloading bag or bulk slurry explosives in deep holes.

4. To evaluate the use of slurry explosives to produce a Deliberate Road Crater (DRC) by comparing the crater dimensions resulting from detonating both identical and equivalent quantities of an aluminized slurry in plastic bags versus 40-lb ammonium nitrate canisters.

5. To test the feasibility of modifying the DRC design to accommodate slurry explosives with a view toward reducing the number of emplacement holes, and the quantities of explosives required.

6. To compare crater dimensions produced by a 40-lb ammonium nitrate (AN) canister with those produced by a canister of equal weight and approximately the same dimensions of prilled ammonium nitrate and fuel oil (ANFO).

7. To evaluate the airblast and ejecta data from the TNT and slurry detonations to verify troop safety criteria.

8. To evaluate the effectiveness of A.O. II and Diamond Ore IIB[4] craters in terms of their ability to effectively stop or impede the movement of an M-60 Main Battle Tank and other tactical vehicles.

9. To evaluate the cratering effectiveness of the XM-180 Cratering Demolition Kit in a clay shale compared to the standard DRC design.

The Fort Peck Reservoir area was selected because of several factors. The Bearpaw clay shale is as uniform a geology as is generally available. In addition to the craters produced for Project A.O. II, during the same time frame, seven 1-ton craters were scheduled to be produced with another commercial explosive for Project D.O. IIB. The additional craters in the same medium would enhance Project A.O. II's overall cratering and obstacle effectiveness studies. Also, a considerable amount of data was obtained from cratering experiments that were performed on the reservation in the late 1960's and early 1970's. These experiments included work for Projects Pre-Gondola I,[5] Pre-Gondola II Row-Charge Experiments,[6] Pre-Gondola III Reservoir Connection,[7] and D.O. I and IIA.[3]

SCOPE OF PROGRAM

Project A.O. II comprised four major series, of which three were cratering experiments and the fourth a trafficability experiment. The cratering ability of the explosives evaluated in each series was determined in terms of crater dimensions and obstacle effectiveness. To assist the reader, the scope of these experiments and associated technical programs are briefly outlined in this section.

The major elements of each experiment are shown in Table 1. Series I, the Prechamber (i.e., preconstructed emplacement cavity) or PC Series consisted initially of two three-hole cratering shots, one with 3960 lb of TNT and the other with 3000 lb of an aluminized slurry

Table 1. Summary of Project Armor Obstacle II experiments.

Series		
I[a]	PC-1	One 3-charge row, 1320 lb TNT per charge, 49-ft spacing
	PC-2	One 3-charge row, 1000 lb AL slurry per charge, 49-ft spacing
	PC-3	One 3-charge row, 1320 lb nitromethane per charge, 49-ft spacing
II[b]	DRC-1	One 5-charge row, eight 40-lb AN canisters, 5-ft spacing
	DRC-2	One 5-charge row, eight 40-lb bags of AL slurry, 5-ft spacing
	DRC-3	One 5-charge row, total of 240 lb of poured AL slurry, 5-ft spacing
	DRC-4	One 3-charge row, 120 lb bagged Al slurry per charge, 10-ft spacing
	DRC-5	One 3-charge row, 80 lb bagged Al slurry per charge, 8-ft spacing
III[b]	AN-ANFO-1	Single charge, 40-lb AN canister (Army standard cratering charge)
	AN-ANFO-2	Single charge, 40-lb ANFO (fabricated canister)
	XM-180	Single kit, 150-lb shaped charge and 40-lb warhead
IV	PC-1 and 2	
	DRC-1-5	
	D.O. IIB IT 1-6	Obstacle effectiveness tests
	D.O. IIB 6 meter	

[a]Unstemmed detonations.

[b]Cavities constructed with M3A1 shaped charges.

blasting agent. Midway through the experimental program a field decision was made to add to Series I a third shot with 3960 lb of nitromethane. The PC Series was designed to compare the cratering ability of equivalent quantities of TNT and an aluminized slurry in a specified design and charge configuration.[8] The nitromethane detonation helped to broaden the comparison of commercial explosives to TNT.

The second series, the Deliberate Road Crater (DRC) Series, was designed to evaluate the advantages of using slurry explosives to create a DRC and to compare the cratering ability of equivalent quantities of an aluminized slurry with that of ammonium nitrate canisters. Series II comprised five cratering experiments. The first three experiments were configured according to the Army's standard DRC design[9] which calls for five emplacement holes per shot; into these five holes for the three respective shots were emplaced 1) eight 40-lb ammonium nitrate canisters, totaling 320 lb, 2) an aluminized slurry totaling 320 lb, and 3) aluminized slurry totaling

240 lb. The fourth and fifth experiments of Series II were three-hole shots employing 360 and 240 lb of an aluminized slurry, respectively. These detonations were designed to test the feasibility of using slurry explosives to produce a DRC with smaller or larger charge weights and greater hole spacings.

Series III was the Ammonium Nitrate/Ammonium Nitrate-Fuel Oil series (AN/ANFO). This series consisted initially of two small cratering shots; one 40-lb AN cratering charge and one 40-lb prilled (small porous round pellets) ANFO canister. The AN/ANFO Series was designed to compare the resulting crater dimensions from the detonation of the Army's standard 40-lb AN canister with that of a canister of prilled ANFO. As a special feature, the firing of an XM-180 Cratering Demolition Kit was added to the third series. The XM-180 is presently being tested and evaluated by the Army Material Command (AMC) as an expedient cratering device to improve the Army's present cratering capability. The kit contains a 15-lb shaped charge for creating the emplacement hole and a 40-lb warhead assembly which serves as the main charge.[10]

Series IV comprised 14 individual tests which evaluated the effectiveness of the seven craters produced for Series I and II, as well as six other 1-ton craters and a 17-ton crater produced in conjunction with Phase IIB of Project Diamond Ore. An M-'8 and an M-60 battle tank and several ordnance tactical vehicles were used to conduct the obstacle effectiveness study. The tests were not part of a detailed military vehicular mobility study. They were designed to evaluate the craters as go/no-go obstacles by driving the selected test vehicles into the crater area and simply determining the point at which each vehicle was stopped.

In support of the four cratering and obstacle effectiveness experiments, a number of technical programs were also conducted. Seismic measurements (surface ground motion), airblast observations, missile studies, crater measurements and technical photography were the main programs conducted. The results of the major technical programs are discussed in greater detail in Chapter 3.

SITE LOCATION AND DESCRIPTION

The sites for A.O. II experiments were situated adjacent to the Fort Peck Reservoir in northern Montana in the vicinity of the Duck Creek Inlet, approximately 11 miles southwest of the Fort Peck Dam and 10 miles north of the Pines Recreation Camp. Figure 1 depicts the general location of the A.O. II and D.O. IIB test site. As shown, the A.O. II test area was about 2 miles northwest of the Pre-Gondola test site.[5] The nearest inhabited dwellings were approximately 4 miles from the test area. Figure 2 is a reproduction of a USGS map illustrating the Control Point (CP) and ground-zeroes for the D.O. and A.O. II detonations. It is apparent from Fig. 2 that all of the cratering shots were conducted in a broad flat valley. The area contains sparse vegetation that supports only limited cattle grazing, which is managed by the Department of Interior, Bureau of Land Management. The test site lies on Corps of Engineer controlled land, but also

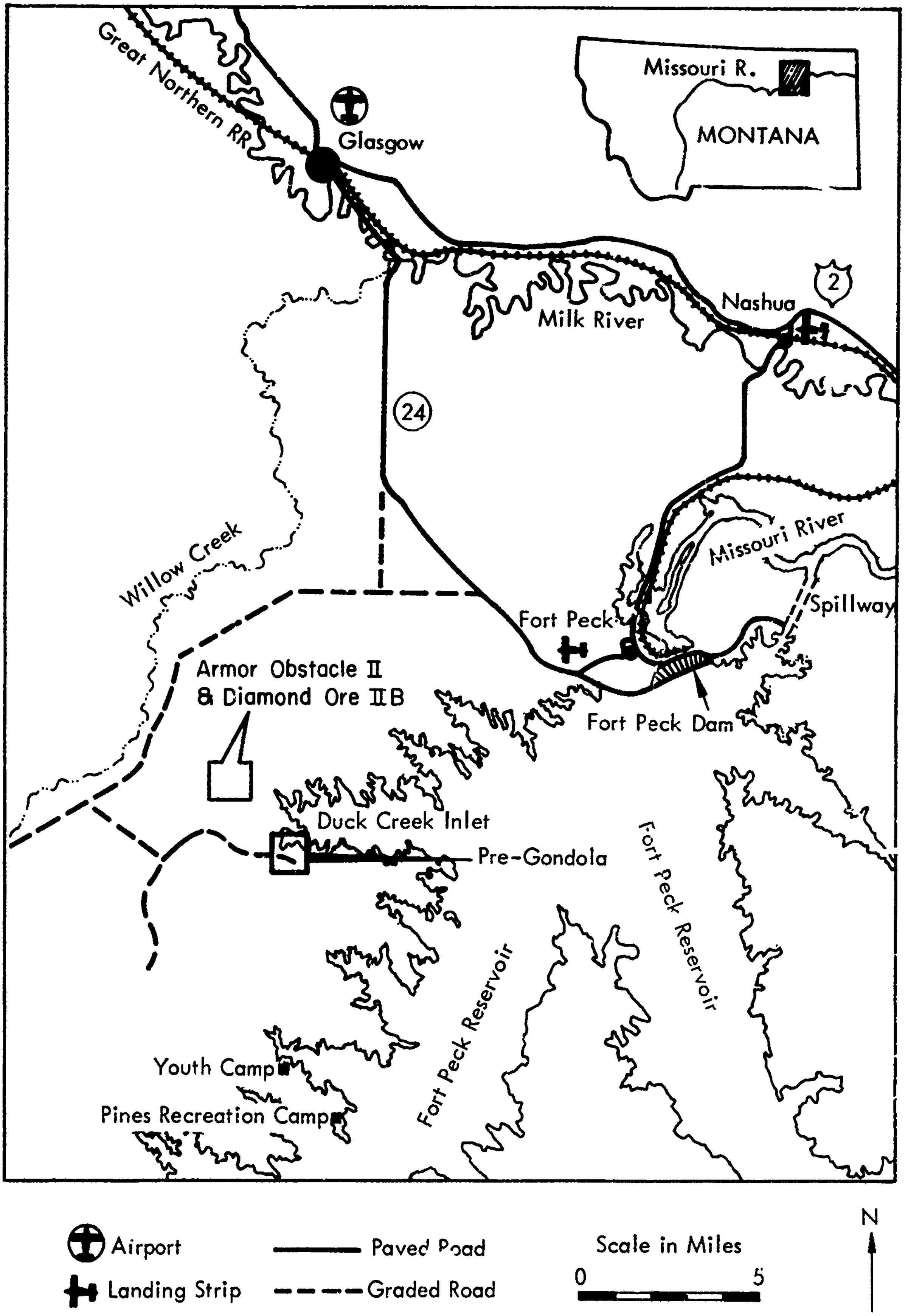


Fig. 1. Project Armor Obstacle II and Diamond Ore IIB site locations.

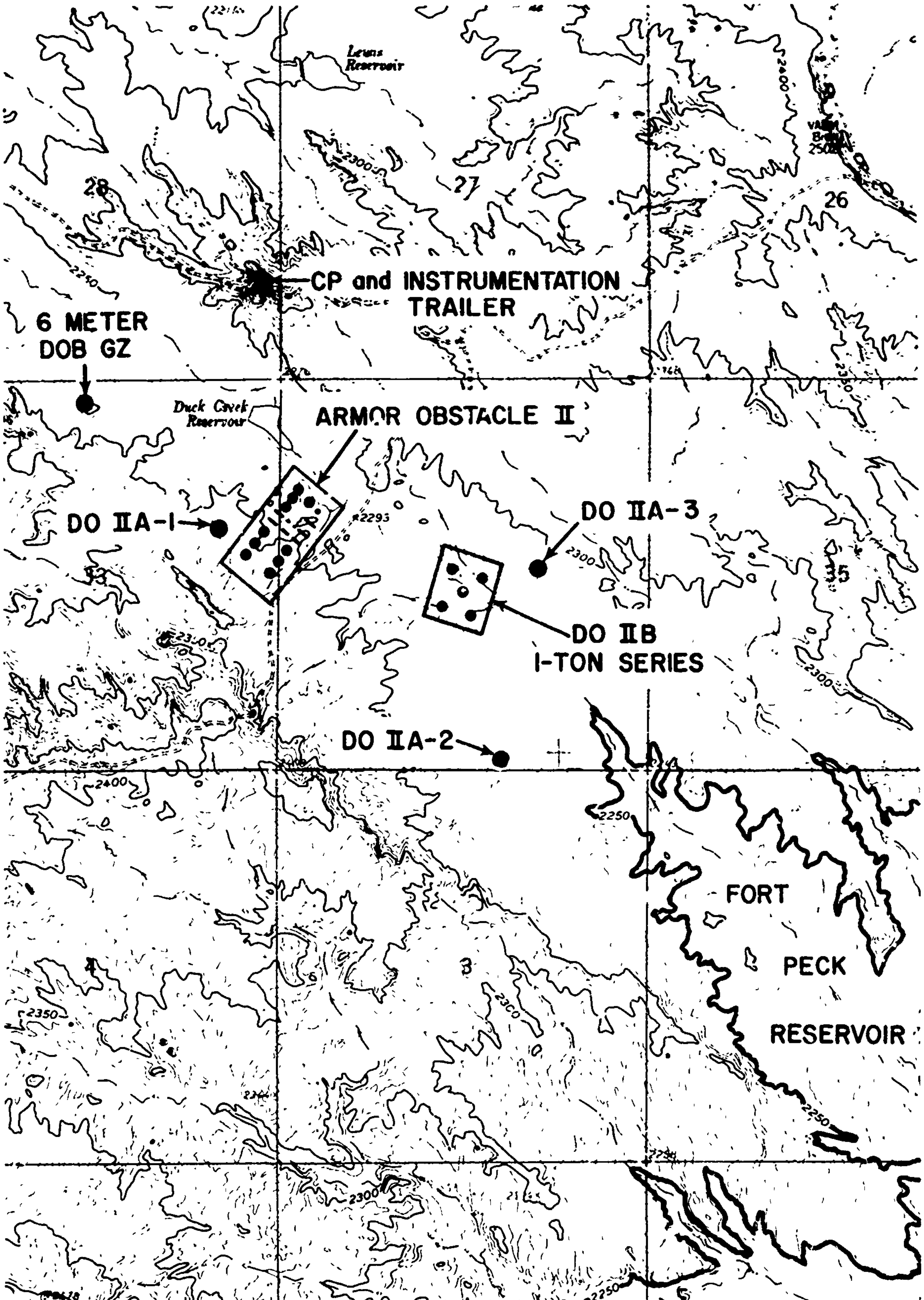


Fig. 2. Armor Obstacle II and Diamond Ore IIB control point and ground zero locations.

falls within the Charles M. Russel Wildlife Refuge. This refuge is administered by the Department of Interior, Bureau of Sport Fisheries and Wildlife. The Fort Peck site is located in Bearpaw shale, a highly compacted, uncemented clay shale of the Cretaceous Age. Where the Bearpaw shale outcrops, it forms either badlands or a terrain with moderately steep to gentle slopes.

An extensive geologic investigation of the test- and surrounding-areas was conducted in 1969 and 1971 in conjunction with the Pre-Gondola series and Phase IIA of the D.O. Project.[4,5] These investigations revealed that the shale at the A.O. II test site is uniform, dark grey, highly compacted and uncemented. It contains infrequent calcareous and iron-manganese concretions up to several feet thick, and waxy, light grey to tan bentonite layers up to several inches thick.

Several joint sets with inconsistent orientation occur at spacings of 1/2 to 3 ft, and numerous hair-line cracks are visible between the major joints. The shale is quite weathered to depths of 10 to 30 ft, and it has the following average physical properties:

Dry density	120 lb/ft^3
Wet density	96 lb/ft^3
Plastic limit	21%
Liquid limit	80%
Moisture content	25%
Unconfined compressive strength	250 psi

The surface layers of the weathered shale are highly fragmented. Alternate wetting and drying cycles have produced a further breakdown of the shale particles to form a fat clay. As a result, the fallback material that made up the crater lips and that constituted the eject fields was very flat, light and brittle.

Chapter 2. Experimental Procedures

SERIES 1, PRECHAMBER SERIES (PC)

In order to compare the cratering ability of TNT to produce a specific obstacle with equivalent quantities of an aluminized slurry and nitromethane, three row-charge detonations consisting of three charges each were performed.

Prechamber Detonation No. 1 (PC-1)

The emplacement chambers for the PC-1 detonation were constructed by a civilian contractor using a Caldwell Model 150A truck-mounted rotary drill with a 30-in. bucket as shown in Fig. 3. Each emplacement hole was drilled to a depth of 20 ft and an initial diameter of 30 in. to facilitate the design requirements illustrated in Fig. 4. The design specifications called for a 24-in. inside diameter concrete culvert to line the emplacement cavities. The culverts installed came in 36-in. long sections with a wall thickness of 3 in. and outside diameter of 30 in. Before installing the culverts, the three emplacement cavities were reamed out an additional 3 in., increasing the final diameter of the chamber to 33 in. A total of 1320 lb of TNT was loaded into each of the three holes for PC-1. The TNT was cast into 3-in.

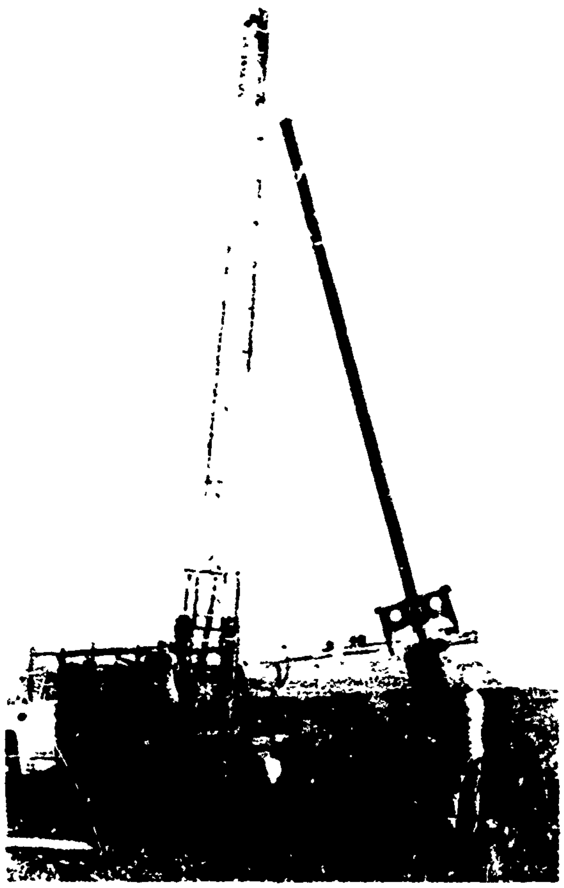


Fig. 3. Bucket auger constructing emplacement chambers for prechamber series.

thick, 55-lb cylindrical charges, 23-1/2 in. in diameter with a 4-in. hole in the center as shown in Fig. 5. Four 1-lb precast DuPont HD-60 boosters were placed in the center of the TNT charges and staggered up the explosive column (see Fig. 6). The material the TNT charges were packed in was a light inert ingredient called vermiculite. The vermiculite was poured down the center of the charge column between the boosters to keep them separated as shown in Fig. 4. Several 7-ft steel cages were fabricated for loading and lowering the TNT cylinders into the emplacement cavities. Each TNT cylinder was hand loaded into the cage above the surface at ground zero. The drill rig used to construct the emplacement holes was also used to lower the explosive charges as shown in Fig. 7. The three charge columns were fired simultaneously. The detonating cords from each chamber were tied into a main firing line which led to the control point situated 3150 ft northwest.

Prechamber Detonation No. 2 (PC-2)

The design and construction of the three chambers for the PC-2 (slurry) detonation were identical to the PC-1 chambers. Instead of the TNT cylinders, 1000 lb of an aluminized slurry in 40-lb plastic bags was loaded into each cavity as illustrated in Fig. 8. An 8-ft 18-in. corrugated culvert was employed as a slurry loading container in one of the three PC-2 chambers. Each of the other two cavities was hand loaded by lowering five bags with a nylon cord to the bottom of the chamber to act as cushion for the remaining bags which were subsequently dropped in. One of the five bags initially lowered contained a one-lb booster identical to the ones used in the PC-1 event. After dropping in 15 bags, another 1-lb booster was placed in one of the remaining five bags which were lowered onto the top of the charge column. The detonating cords that led to the boosters were tied off at the ground surface to keep them from falling into the chamber. Each detonating cord was shielded with 1-in. tubing to prevent the bags of slurry from igniting prematurely. Simultaneous detonations were also used for the PC-2 chambers.

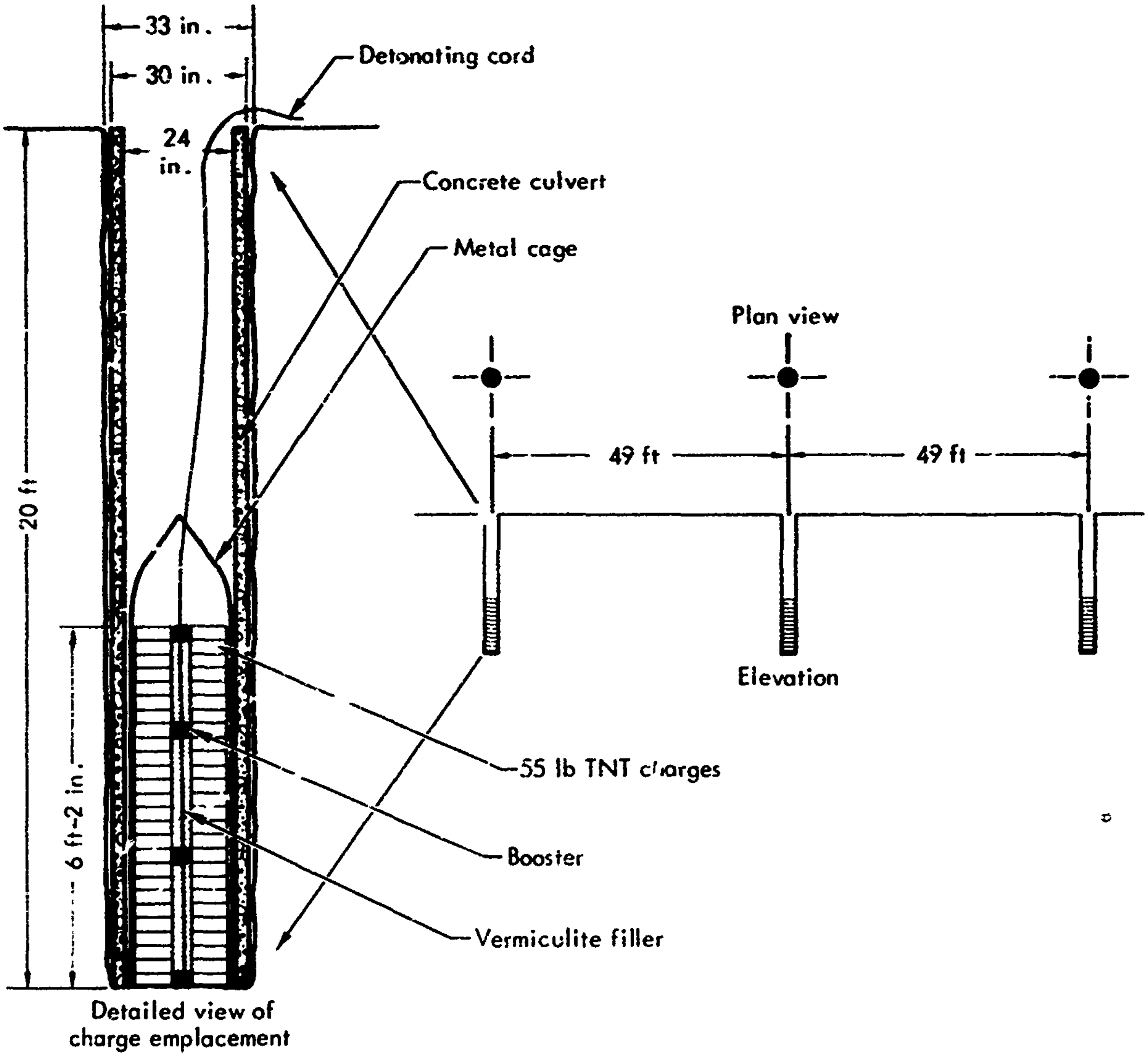


Fig. 4. Emplacement chamber for PC-1 (TNT).

Fig. 6. Booster and charge configuration for PC-1 detonation.

Fig. 5. 55-lb TNT cylindrical charge.

Fig. 7. Loading operation for Prechamber Series 1 (TNT).

Prechamber Detonation No. 3 (PC-3)

An excess of nitromethane from previous programs conducted at Fort Peck, along with a small quantity left over from the D.O. IIB detonation, provided enough explosive to model PC-1 (TNT) with the PC-3 (nitromethane) as shown in Fig. 9. The contractor's rotary drill rig was also used to construct the required emplacement cavities. Because this shot was not included in the initial technical concept for this experimental series, concrete culverts were not available to line the PC-3 emplacement chambers. The nitromethane was loaded in 55-gallon drums that had an outside diameter of 24 in. Because the chambers were not lined, the 30-in. diam emplacement cavity was sufficient. Preparing and loading the nitromethane charges for the PC-3 detonation was a relatively simple operation. A total of 1320 lb of the liquid explosive was loaded into each cavity. Each of the three explosive columns consisted of three 55-gallon drums with the top drum weighing only 320 lb compared to the 500 lb in the two lower drums. Instead of attempting to lower the drums and taking the chance of dropping one, the empty drums were lowered individually into the chambers with a 2-lb booster of C-4 taped to the side of each (see Fig. 10). A rubber hose was placed in the large hole of each empty drum which allowed the nitromethane to be fed from the storage drums into the downhole drums (Figs. 11 and 12). The three cavities were fired simultaneously, but only two of the charges detonated. Charge "A," (see Fig. A-9) was later detonated as a single shot after digging down close to the top of the second 55-gallon drum and adding 100 lb of excess explosive.

SERIES 2, DELIBERATE ROAD CRATERS (DRC)

To evaluate the effectiveness of producing DRC's with slurry explosives, a total of five detonations were conducted. Forty-pound shaped charges fired from a 12-in. standoff were used to make the emplacement holes for DRC-1, 2 and 3. Because military blasting caps were unavailable, commercial 1-lb precast boosters and detonating cord seated in a small quantity of C-4 were used to detonate the shaped charges, as shown in Fig. 13. The shaped charges were fired

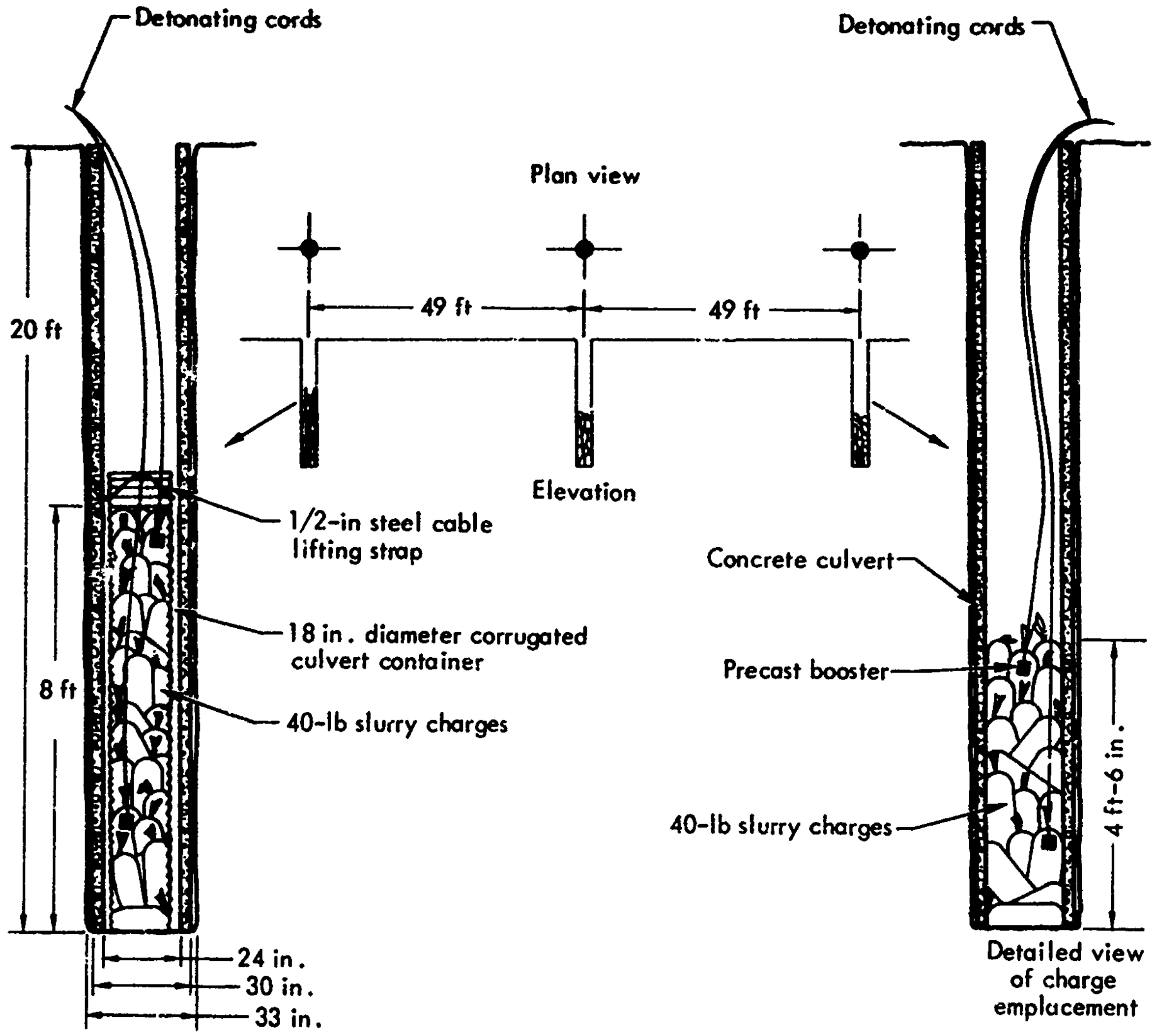


Fig. 8. Emplacement chamber for PC-2 (Al slurry).

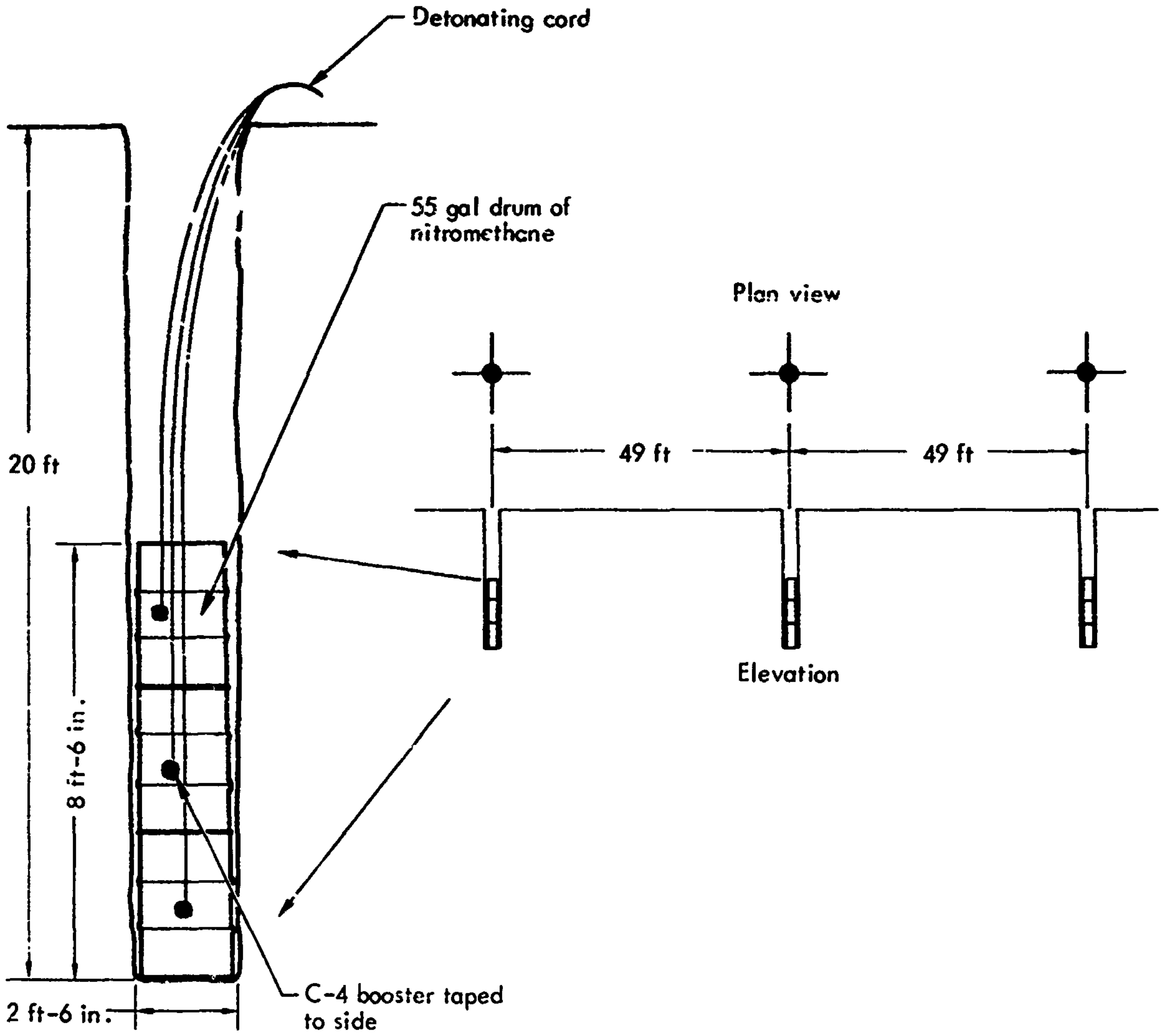


Fig. 9. Emplacement chamber for PC-3 (nitromethane).

Fig. 10. C-4 Booster being taped to empty 55-gallon drum for nitromethane detonation (PC-3).

Fig. 11. Lowering empty 55-gallon drum and rubber transfer hose.

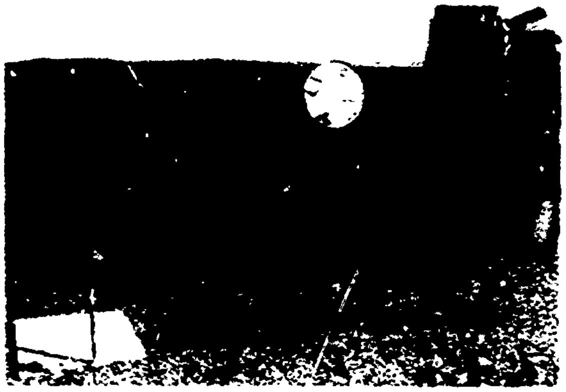


Fig. 12. Feeding nitromethane from storage drum to down-hole drums for PC-3 detonation.

in groups of five for the specific DRC designs. In very few instances did the 40-lb shaped charges produce an emplacement hole in the clay shale medium that met the design specifications and did not require subsequent hand excavation. The average depth and bottom diameter of the emplacement holes produced was 4 ft 6 in. and 5 in. respectively. Detailed results on the performance of the shaped charges are presented in Table 2. The standard posthole digger and hand auger were used

Table 2. Shaped charge results.

Detonation	Charge size (lb)	Standoff height (in.)	Depth[a] Observed (in.)	Penetration (in.)	Hole diameter[b] Top (in.)	Bottom (in.)
Trial No. 1	40	12	36	—	12	4.7
Trial No. 2	40	48	62	—	11	3.5
Trial No. 3	40	48	57	—	11.5	4.2
DRC-1	40	12				
A	40	12	38	52	18	9.0
B	40	12	54	63	19	8.5
C	40	12	48	59	21	8.5
D	40	12	44	60	22	8.0
E	40	12	58	69	20	8.5
DRC-2	40	12				
A	40	12	56	67	17	8.0
B	40	12	55	60	16	8.0
C	40	12	55	64	16	7.5
D	40	12	54	60	17	8.0
E	40	12	55	62	18	8.5
DRC-3	40	12				
A	40	12	58	64	13.5	8.5
B	40	12	60	68	14	8.0
C	40	12	64	69	15	9.0
D	40	12	60	67	15	8.0
E	40	12	50	60	17	8.5

[a]Depth to which material can easily be removed from the hole.

[b]Hole diameter after removal of fallback material and excavation to design depth. Average top and bottom diameters before excavation were 12 and 5 in. respectively. Note: Trial charges were not excavated.

Fig. 13. Preparing 40-lb shaped charge to produce an emplacement hole for DRC Series.

to remove a major portion of that material fractured by the shaped charge that was not extruded from the holes. Neither the posthole digger nor the hand auger were long enough to clean out the debris in the 7-ft emplacement holes. Therefore, a 3-ft extension was added to the hand auger (Fig. 14). The emplacement holes for DRC-4 and 5 were constructed with the small tractor-mounted 8-in. diam auger illustrated in Fig. 15. The designs for the DRC's are illustrated in Figs. 16-20. The ammonium nitrate canisters used in the DRC-1 detonation were lowered into each emplacement hole by two men with a strand of nylon cord (Fig. 21). Detonating cord was used to ignite the top canister in each of the five emplacement holes. The remainder of the DRC shots were conducted with slurry explosives. The top bags of slurry in each of the emplacement holes for DRC-2, 4 and 5 were primed with a 1-lb precast

Fig. 14. 3-ft extension on hand auger for extending emplacement holes to 7 ft.

Fig. 15. Tractor-mounted 8-in. auger drill.

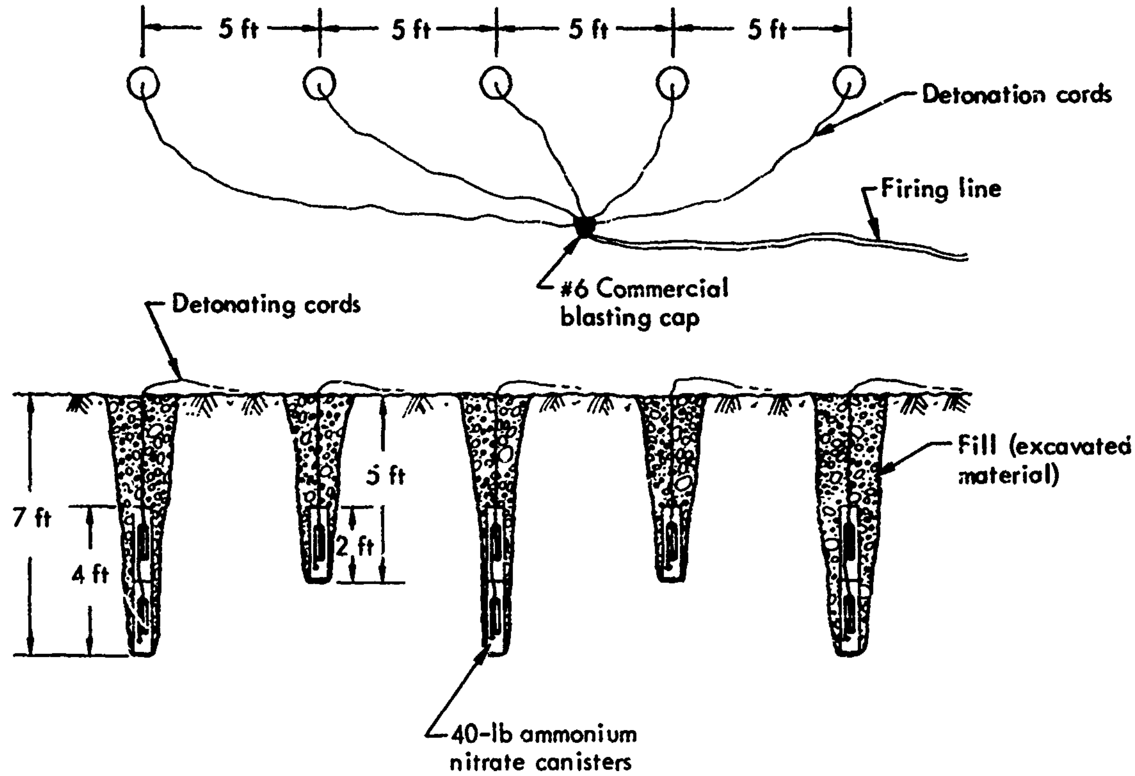


Fig. 16. Emplacement configuration for DRC-1 (40-lb AN Canister).

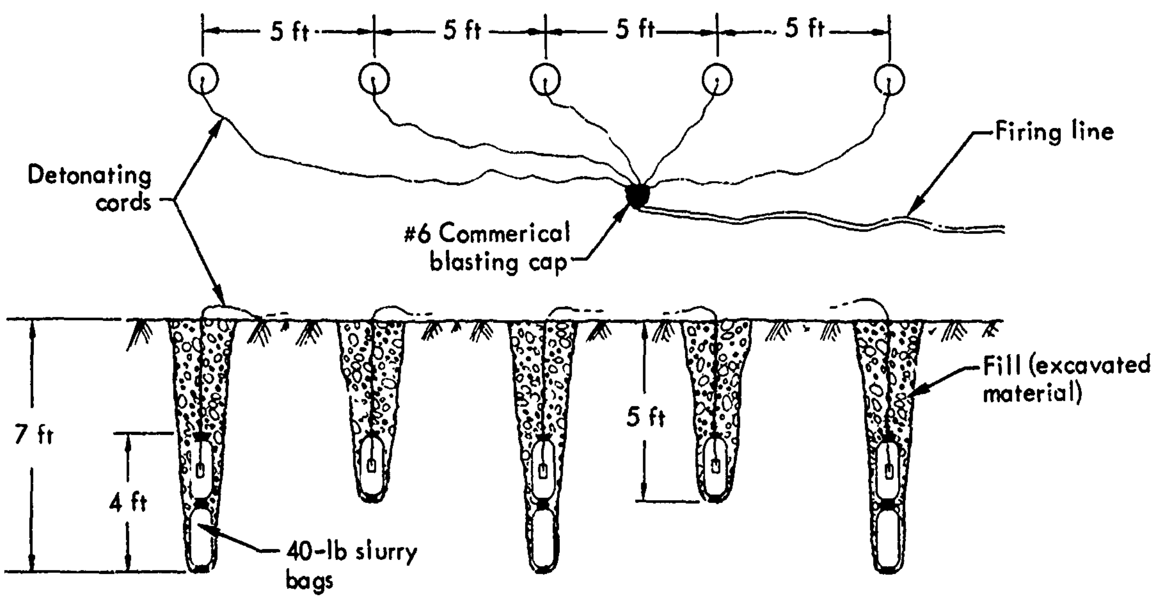


Fig. 17. Emplacement configuration for DRC-2 (40-lb Al slurry bags).

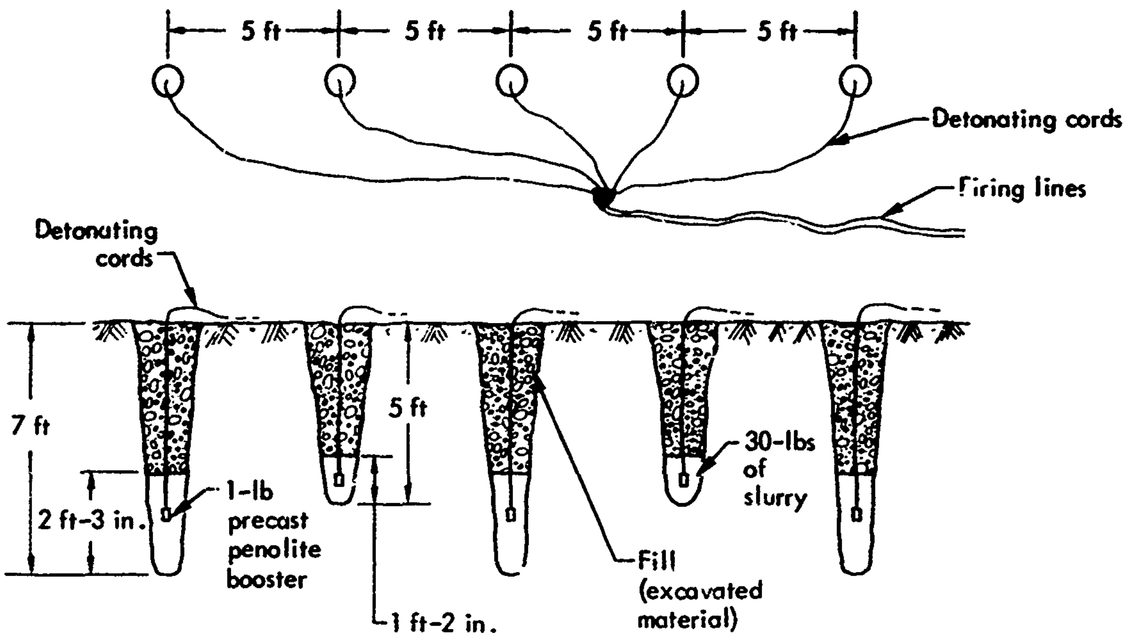


Fig. 18. Emplacement configuration for DRC-3 (poured slurry).

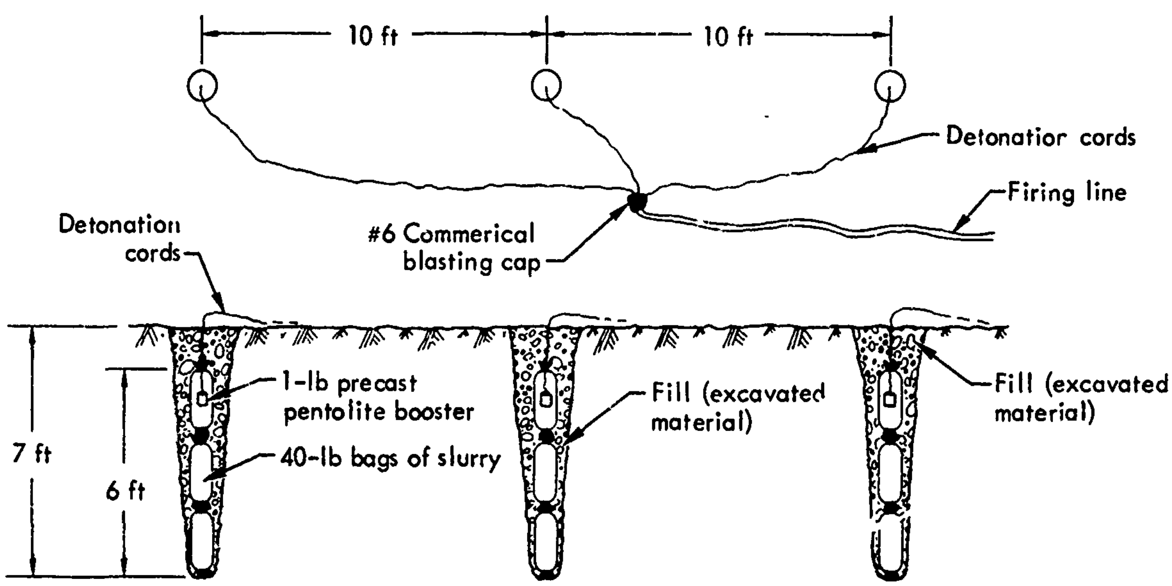


Fig. 19. Emplacement configuration for DRC-4 (40-lb Al slurry bags).

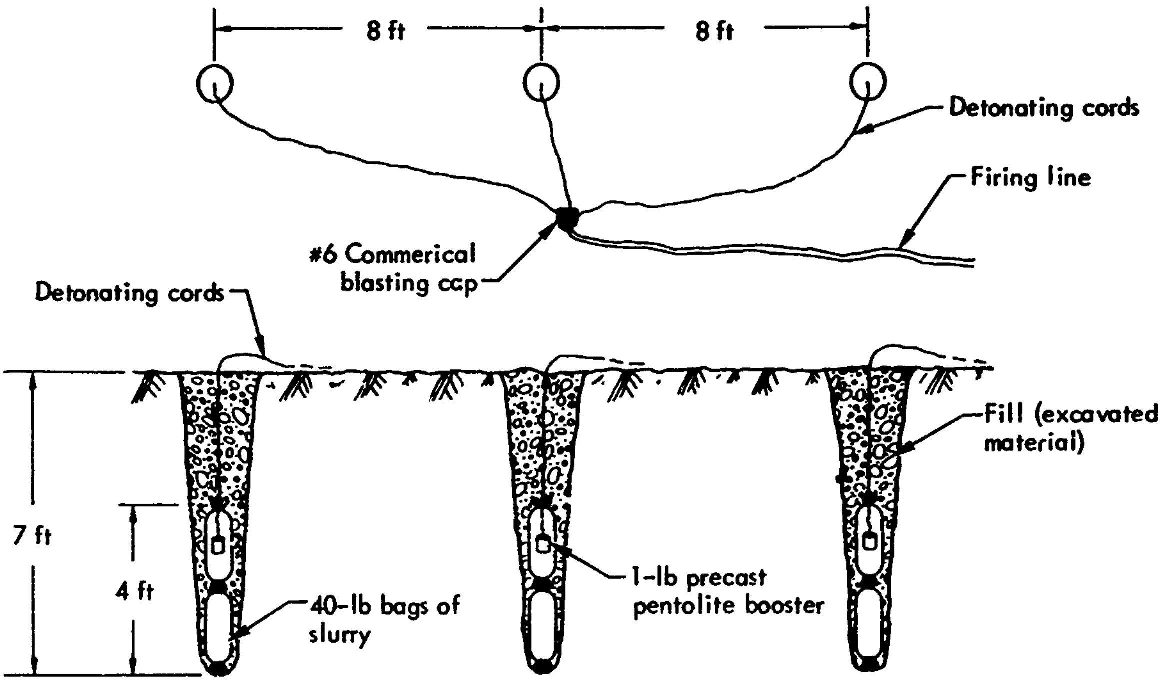


Fig. 20. Emplacement configuration for DRC-5 (40-lb Al slurry bags).

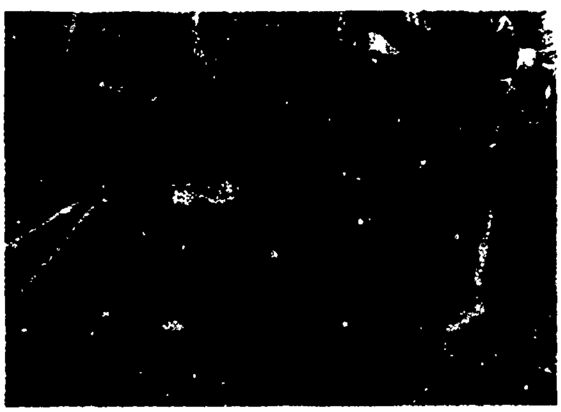


Fig. 21. Loading of 40-lb ammonium nitrate canister into DRC-1 emplacement hole.

Fig. 22. Pouring slurry explosive into DRC-3 emplacement hole.

booster and detonating cord. After pouring the slurry into the five emplacement holes for DRC-3, as shown in Fig. 22, the handle of a shovel was used to push a hole in the top of each charge column before emplacing a 1-lb booster and detonating cord. After loading the explosive

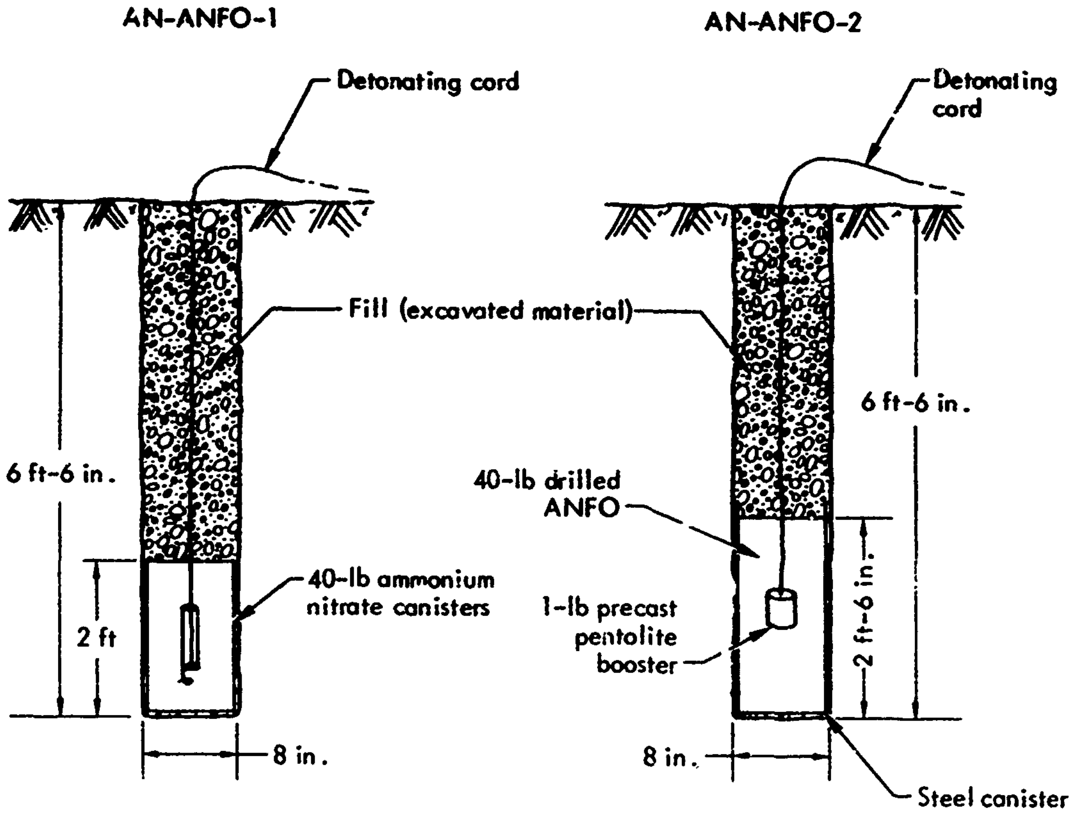


Fig. 23. Emplacement configuration for AN-ANFO 1 and 2 (40-lb AN Canister and 40 lb of prilled ANFO).

charges, the emplacement holes for the DRC series were stemmed with the material excavated from the cavity. The charges in each of the DRC detonations were set off simultaneously.

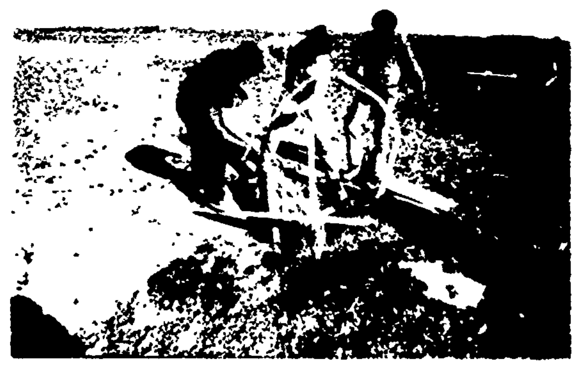


Fig. 24. Loading of fabricated ANFO Canister (AN-ANFO 2).

SERIES 3, AMMONIUM NITRATE/ AMMONIUM NITRATE FUEL-OIL (AN/ANFO)

The first half of Series III was comprised of two small cratering shots that were conducted for a comparison of the cratering effectiveness of the Army's standard 40-lb cratering charge and a 40-lb charge of prilled ammonium nitrate and fuel oil. The emplacement holes for these two detonations were also made with the small tractor-mounted auger. They were drilled to a depth of 6 ft 6 in., as illustrated in Fig. 23. To overcome the hydroscopic properties of ANFO, a steel canister, similar in dimensions to the Army's standard AN canister, was fabricated to contain the ANFO. The ANFO container was loaded on-site and

placed into the emplacement hole by the same procedures used to emplace the 40-lb cratering charges (Fig. 24). A 1-lb booster was used to detonate the prilled ammonium nitrate charge, while the 40-lb cratering charge was initiated with detonating cord. The final portion of this series consisted of firing the Demolition Kit, Cratering XM-180, illustrated in Fig. 25. A technical advisor

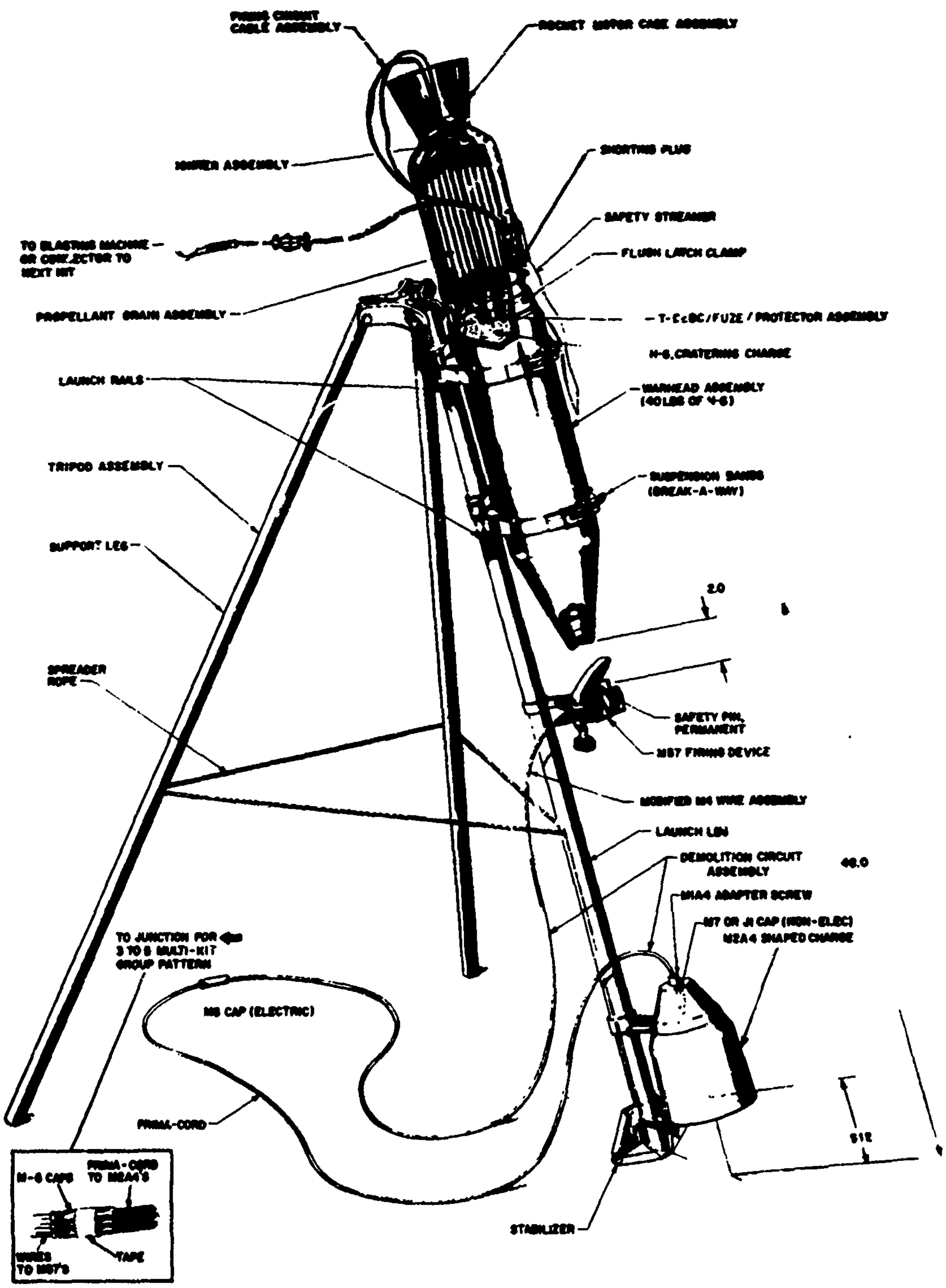


Fig. 25. Demolition Kit, Cratering, XM-180 (from Ref. 10).

from Picatinny Arsenal, assisted by two EERL personnel, unpacked, set up, and fired the experimental cratering kit.

DESCRIPTION OF TECHNICAL PROGRAMS

Before describing the test conducted in the fourth series, it is appropriate to discuss here the technical programs conducted in conjunction with the three cratering series just described. The results of these technical programs are presented in Chapter 3.

Ground and Aerial Surveys

Pre- and postshot ground surveys and aerial photography were taken at ground zero of the PC craters (Series I). Procuring topographic data for the DRC and the AN-ANFO Series (Series II and III respectively) was limited to ground surveys. Ground pre- and postshot surveys were made using conventional survey techniques by a survey team from the Omaha Engineer District. The aerial photography was done by Limbaugh Engineers, Inc., from Albuquerque, New Mexico, to produce pre- and postshot topographic maps and isopachs.

Air Overpressure Measurements

The air overpressure measurements (airblast) were taken by the Sandia Laboratory, Albuquerque (SLA) with their own instrumentation. The objective of the program was to determine the peak airblast amplitude for the eight detonations that comprised the PC and DRC series and determine if the recorded readings fell within existing troop safety distances. The overpressure gages used were Statham unbonded strain gages and Dynesco bonded strain gages. Gage signals were telemetered from each station to the A.O. II control point where the signals were recorded on an Ampex CP100 14-track recorder. After each detonation, records were played back in the field to compare measured and predicted peak amplitudes so that required field adjustment of the equipment could be accomplished. Measurements were made at three stations for each detonation. Each station utilized two gages to provide a high-range and low-range measurement capability.

Seismic Investigation

Surface ground motion measurements were measured by the Soils and Pavements Laboratory (S&PL) of the WES. The purpose of these measurements was to obtain additional data on multiple-charge detonations at varying charge weights and depths of burial.

Four recording stations were operated for each detonation. Each station consisted of three orthoganally oriented geophones to monitor motion in the radial, transverse, and vertical directions with respect to each surface ground zero. The geophones were the Model L1-3D, with a sensitivity of 0.65 volts/cm/sec, and the Model HS-10-1, with a sensitivity of 3.00 volts/cm/sec. The motion components were recorded at each station with a six-channel Century 444 Oscillograph. A separate channel recorded the actual zero time mark that was manually activated on a voice cue from the A.O. II control point.

Each geophone was placed in a hole excavated slightly below the ground surface. The hole was subsequently back-

filled with the excavated material and carefully tamped in layers to maintain proper geophone orientation and to duplicate the original soil density. Additional soil was placed on the top of the emplaced geophones forming a ballast mound approximately 8 in. high and 40 in. in diameter. Orientation of the geophones, relative to each detonation, was established by compass and visual observation. Additional data on the geophones employed and the location of the siesmic stations are presented in Fig. 26 and Table 3.

Missile Study

Following each detonation, data on the maximum missile range and missile distribution were collected. The missile distribution data was accumulated by a conventional ground survey and by counting the number of missiles which fell within two 750-lb, 15-deg sectors. Each sector was surveyed from the center and end charges and oriented perpendicular and parallel to the main axis of the row, respectively, as illustrated in Fig. 27. Stakes were placed at 50-ft intervals along the boundaries of the sectors, creating sections with known areas. The total number of missiles with diameters of 2 in. or larger that landed within each section was located. The probability of a missile hit per square foot within the section was then determined by dividing the number of missiles in a section by the area of that section. Missile data from the parallel sectors of PC-1 and -3 and DRC-2 and -5 as well as the perpendicular sectors of PC-1 and -3 and DRC-4 were not taken because a large amount of debris ejected by early shots made complete and accurate data recovery impossible.

Table 3. Seismic station and shot point coordinates for A.O. II.

	Coordinates (ft)	
	X	Y
Seismic Station		
2	2,690,483	364,504
3A	2,690,221	363,727
4B	2,685,949	364,682
5	2,683,610	360,547
6B	2,683,000	354,451
Shot Point[a]		
PC-1	2,690,460	364,639
PC-2	2,690,581	364,590
PC-3	2,690,538	364,916
DRC-1	2,690,478	364,788
DRC-2	2,690,568	364,758
DRC-3	2,690,658	364,728
DRC-4	2,690,499	364,866
DRC-5	2,690,690	364,801

[a]Series PC and DRC were multiple charge detonations; the coordinates tabulated are for the center charge.

Technical Photography

The objective of this program was to document the major phases of the experimental programs, to include emplacement hole construction, explosive emplacement, the detonation sequence, the craters formed by the detonations and the mobility and obstacle effectiveness study. In addition to the still photos taken with a motor-driven Bessler Topcon 35 mm camera, two types of motion picture photography were utilized. Two high-speed (500 and 1000 frames per sec) Redlake Hycam movie cameras, located 1000 ft and 2500 ft away from ground zero were used to record the cloud formation for each of the PC and DRC detonations. A

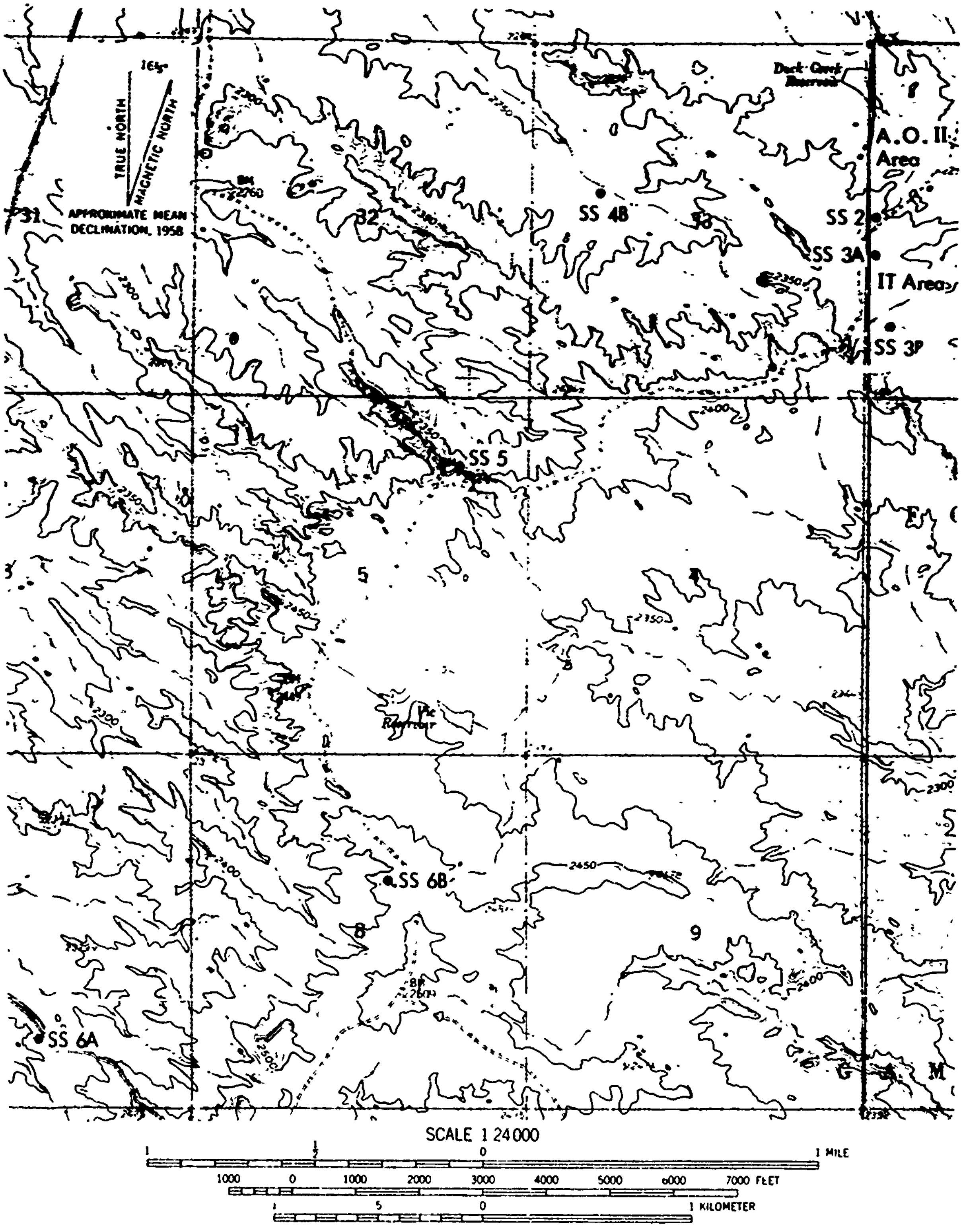


Fig. 26. Seismic station locations for detonations in the A.O. II area.

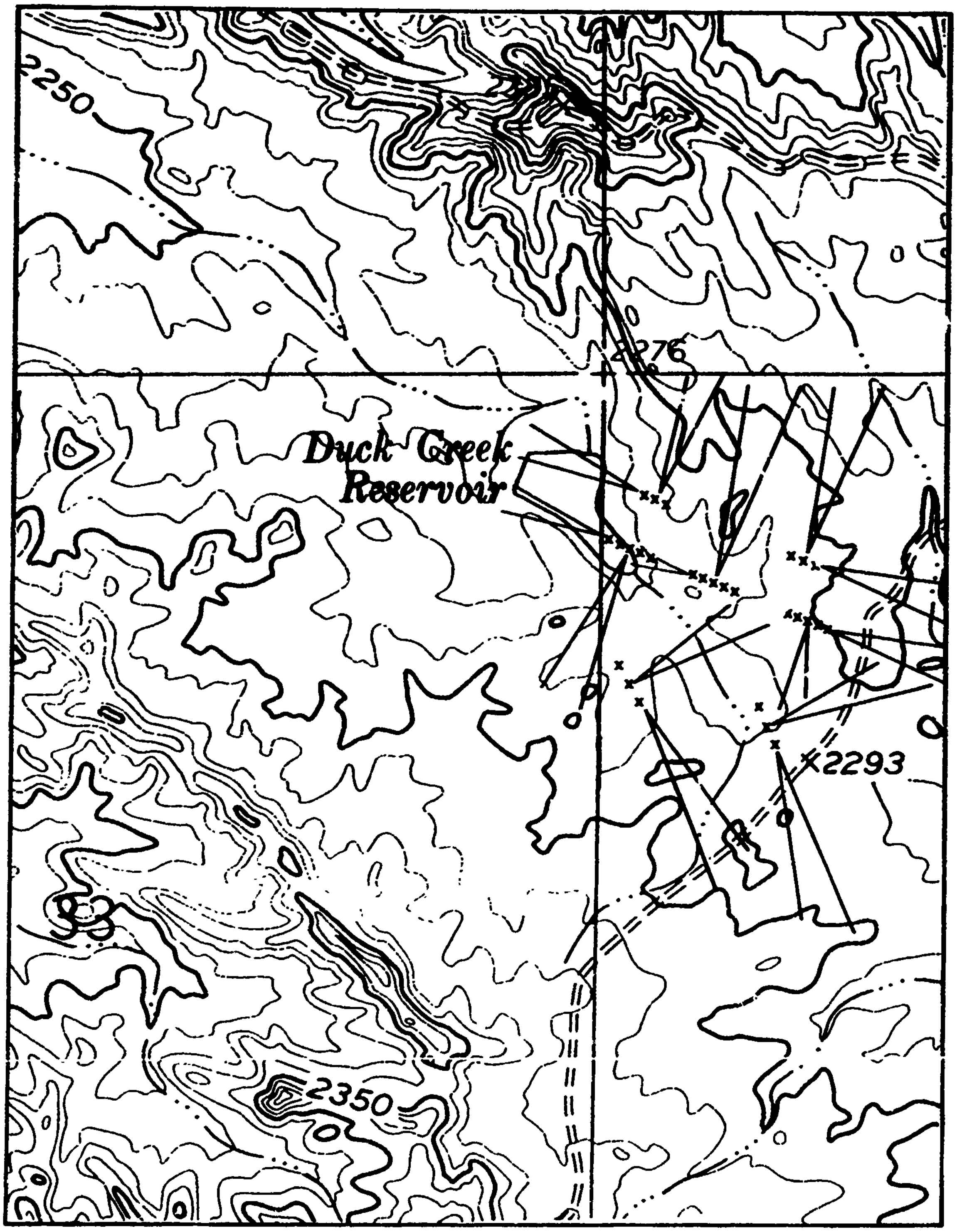


Fig. 27. Missile study sectors. (All sectors extend 750 ft from ground zero and subtend an angle of 15 deg.)

standard speed 16 mm Canon Scopic camera was used to record the drilling and loading operations preceding the actual detonations and the events associated with the obstacle effectiveness study.

Explosive Property Verification

The aluminized slurry used for Project A.O. II was manufactured by the Dow Chemical Company, low bidder on a competitive contract. Included in the contract

specifications for the slurry was a requirement that certain physical properties of the slurry be tested and the results reported to ensure that the mix did meet the minimum specifications. Dow measured the pressure and energy performance of the slurry at its underwater test site in Minnesota using essentially the methods and procedures reported in Refs. 11 and 12. The detonation velocity was measured in a piece of Schedule 40 steel pipe, above ground using self shorting pins. In addition to the tests conducted by the manufacturer, the Organic Materials Division of the Chemistry Department at the Lawrence Livermore Laboratory (LLL) was requested by EERL to run a detonation velocity test on the experiment slurry mixture. This test was conducted at the A.O. II test site at Fort Peck, Montana, on October 24, 1972. A total of 55 lb of explosive was detonated in a buried 6-in. by 36-in. Schedule 40 steel pipe using a 1-lb Dupont Pentolite booster, 7 ft of 100 grain/ft PETN primacord, and an RP-1 high energy detonator. The detonation velocity was measured with a 6-pin (Bi TO_3 crystal) rate stick. The pins were located at approximately 2-in. intervals. The first pin was positioned 24 in. from the booster to avoid measurement of the booster overdrive and to give time for the HE to reach detonation stability. The pin signals were recorded on an L-10 raster scope.

SERIES 4, OBSTACLE EFFECTIVENESS STUDY

The majority of the craters produced in the PC and DRC series were tested to determine if they were capable of stopping or significantly delaying the Army's main battle tanks and several other tactical vehicles. In addition to these craters, the seven craters produced in conjunction with Project D.O. IIB were also evaluated. A profile and some of the physical characteristics of the vehicles used to perform this study are illustrated in Appendix C. They included an M-60, the Army's main battle tank, an M-48 tank, an Armored Personnel Carrier, two 2-1/2 ton trucks, and two 1/4-ton trucks. The M-60 tank and crew were obtained from the 1st Battalion, 70th Armor, 7th Infantry Division (Mech) located at Fort Carson, Colorado. C Troop, 1st Squadron, 163rd Armored Cavalry Regiment N.G., located in Glasgow, Montana, provided the M-48 tank and the other tactical vehicles.

To determine the obstacle effectiveness of the various craters, the tactical vehicles made several attempts to enter and exit the craters unassisted. Only the tanks were evaluated in the PC craters. Each tank traversed the long axis through the center of the crater. Most of the vehicles transversed the short axis of the craters produced for the DRC series. The vehicles evaluated in the D.O. craters moved from east to west across the craters simulating approach to an enemy on the western side. In those cases where the vehicle was unable to leave the crater under its own power, it was either towed out or an exit ramp was constructed across the crater with a bulldozer. To assist in the evaluation of this phase of the project, an Armor Officer from the Armor School at Fort Knox, Kentucky, provided technical and operational advice.

As an expedient, a tank stuck in a 50-ft deep crater without any mechanical assistance might conceivably attempt to reduce the slope of the crater by using its gun to blast an exit through the crater lip. As an alternative to this expedient, three holes with an average depth of 4 ft were spaced 5 ft apart in the lip of the 6M D.O. IIB crater and each loaded with 80 lb of explosive in an attempt to reduce the height of the crater slope and provide an easier exit for the tank.

Results of the cratering experiments and the obstacle effectiveness study are presented in Chapter 3.

Chapter 3. Test Results

This chapter presents the results of the cratering test conducted during the PC, DRC, and AN-ANFO events. Results of the technical programs associated with each of the events are also included. In addition, a brief discussion on the results of the obstacle effectiveness test is presented.

GROUND AND AERIAL SURVEYS

Crater measurements were obtained from topographic maps that were produced from aerial surveys and from plots of conventional survey data. Volumes of the craters are based upon cross sectional areas measured with a planimeter and the application of Simpson's rule. In order to adequately evaluate the results of the three cratering programs it is imperative that the reader be familiar with the standard crater nomenclature that appears as Fig. 28.[1]

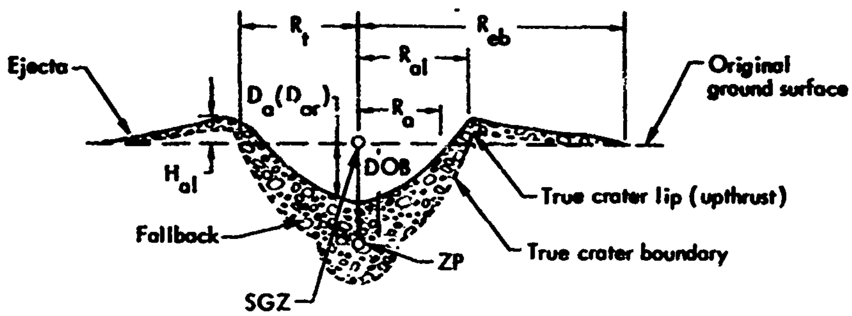
Results of the PC series are given in Table 4. A typical cross section and longitudinal profile of a PC crater are presented in Figs. 29 and 30. Figure 31 is an oblique aerial view of the PC-2 crater. Contained in Appendix A are pre- and postshot topographic maps and isopach maps of the PC-1 and 2 events, as well as cross sections and longitudinal profiles of the other PC detonations. Results of the DRC and AN-ANFO series are presented in Tables 5 and 6. Typical results are shown in Fig. 32. Plots for the remaining elements in Series II are presented in Appendix A. Several of the DRC and AN-ANFO craters are pictured from an oblique aerial view in Fig. 33.

AIR OVERPRESSURE MEASUREMENTS

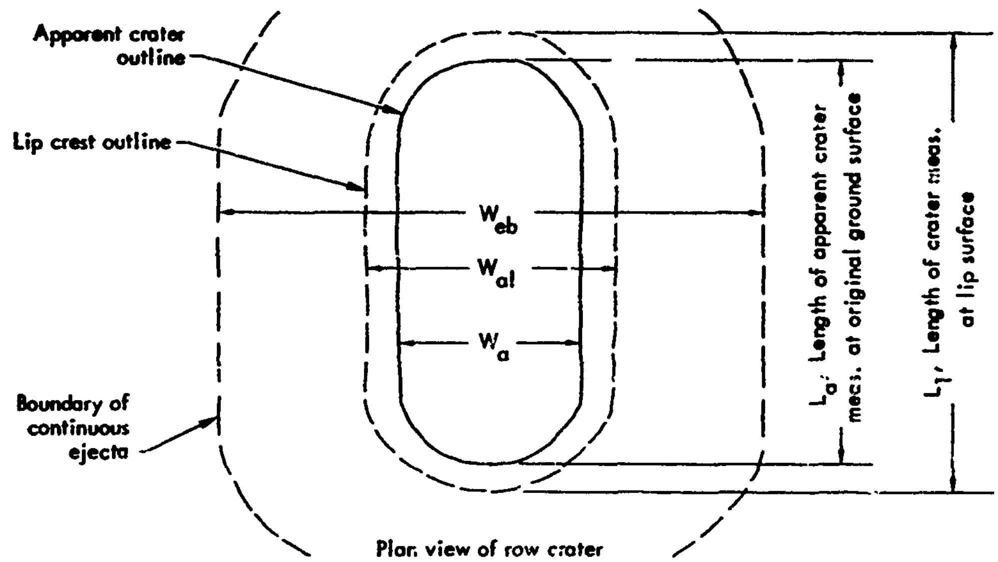
A summary of the observed peak overpressure is tabulated in Table 7 and plotted in Fig. 34. A brief analysis of this information is presented in Chapter 4. Reference 13 presents a thorough analysis of all the airblast data.

SEISMIC MEASUREMENTS

Table 8 summarizes the peak particle velocity measurements obtained for the PC and DRC detonations. These peak values were obtained from oscillograph records of the measured particle velocity as a function of time at each recording station. Plots of the vertical, radial and



Cross section of single-charge or row crater



Plan view of row crater

Nomenclature which applies only to single-charge craters

- R_a - Radius of apparent crater measured at original ground surface datum
- R_t - Radius of true crater measured at original ground surface
- R_{al} - Radius of apparent lip crest
- R_{eb} - Radius of outer boundary of continuous ejecta
- D_a - Maximum depth of apparent crater below and normal to original ground surface

Nomenclature which applies only to row craters

- W_a - Width of apparent linear crater measured at original ground surface datum
- W_{al} - Width of apparent lip crest
- W_{eb} - Width of outer boundary of continuous ejecta
- D_{ar} - Depth of apparent row crater

Nomenclature and definitions which apply to both single-charge and row craters

- H_{al} - Apparent crater lip crest height above original ground surface
- V_a - Volume of apparent crater below original ground surface
- V_{al} - Volume of apparent lip
- V_t - Volume of true crater below original ground surface
- DOB - Depth of burst
- ZP - Zero Point—effective center of explosion energy
- SGZ - Surface Ground Zero (point on surface vertically above ZP)
- NSP - Nearest Surface Point (point on surface nearest ZP; same as SGZ for horizontal surface)

Fig. 28. Crater nomenclature.

Table 4. Armor Obstacle II, PC Series crater measurements.

Detonation	Charge wt/hole (lb)	Explosive	Apparent crater radius, R_a (ft)	Apparent crater depth, D_a (ft)	Apparent lip height, H_{al} (ft)	Radius of apparent lipcrest, R_{al} (ft)	Volume of apparent crater, V_a (ft^3)
PC-1	1320	TNT (55-lb charges 23.5-in. diam 3-in. thick)					
A			20.5	10.3	3.2	27	4383
B			18.7	9.1	3.1	27.5	3657
C			17.5	8.4	3.2	26.3	3260
Average			18.9	9.3	3.2	26.9	3767
PC-2	1000	10% Al slurry (40-lb bags, 7-in. diam 24-in. long)					
A			14	4.6	3.4	22.7	1529
B			11.5	4.3	4.8	23.5	1056
C			14.5	6.8	4.0	24	1800
Average			13.3	5.2	4.1	23.4	1462
PC-3	1320	Nitromethane (55-gallon drums)					
A[a]			18	7.4	6.0	30	2774
B			20	9.5	3.7	28	4053
C			19	9	4	30	3448
Average			19	8.6	4.6	29.3	3425

[a]Charge A was fired separately after failing to detonate with holes B and C.

Table 5. Armor Obstacle II, DRC Series crater measurements.

	DRC-1	DRC-2	DRC-3	DRC-4	DRC-5
Total charge weight (lb)	320	320	240	360	240
Explosive	Ammonium nitrate (AN)	10% Al slurry	Slurry	Slurry	Slurry
Method of emplacement	7-in. diam canisters	7-in. diam plastic bags	Poured	7-in. diam plastic bags	7-in. diam plastic bags
No. of emplacement holes	5	5	5	3	3
Dimension[a]					
Apparent width, W_a (ft)	18.4	14.6	15.6	15.6	13.0
Apparent depth, D_{ar} (ft)	3.9	3.7	3.7	3.8	3.1
Lip height, H_{al} (ft)	1.5	1.9	1.9	1.5	1.6
Lip crest width, W_{al} (ft)	26.0	21.4	22.4	21.2	21.0
Apparent length, L_a (ft)	33	29	34	34.5	29
Lip crest length, L_1 (ft)	40	32	36	40	33
Total apparent volume, V_a (ft^3)	1253	771	774	894	521

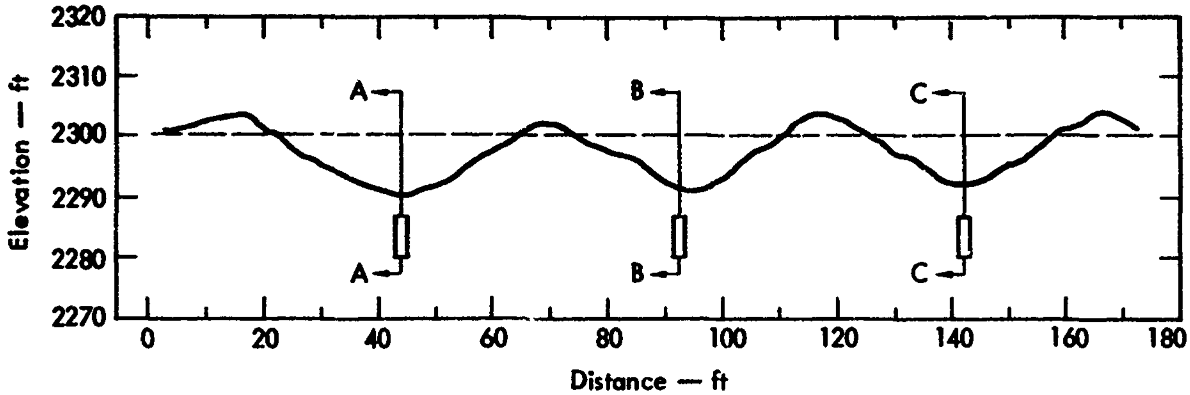


Fig. 29. PC-1 longitudinal profile.

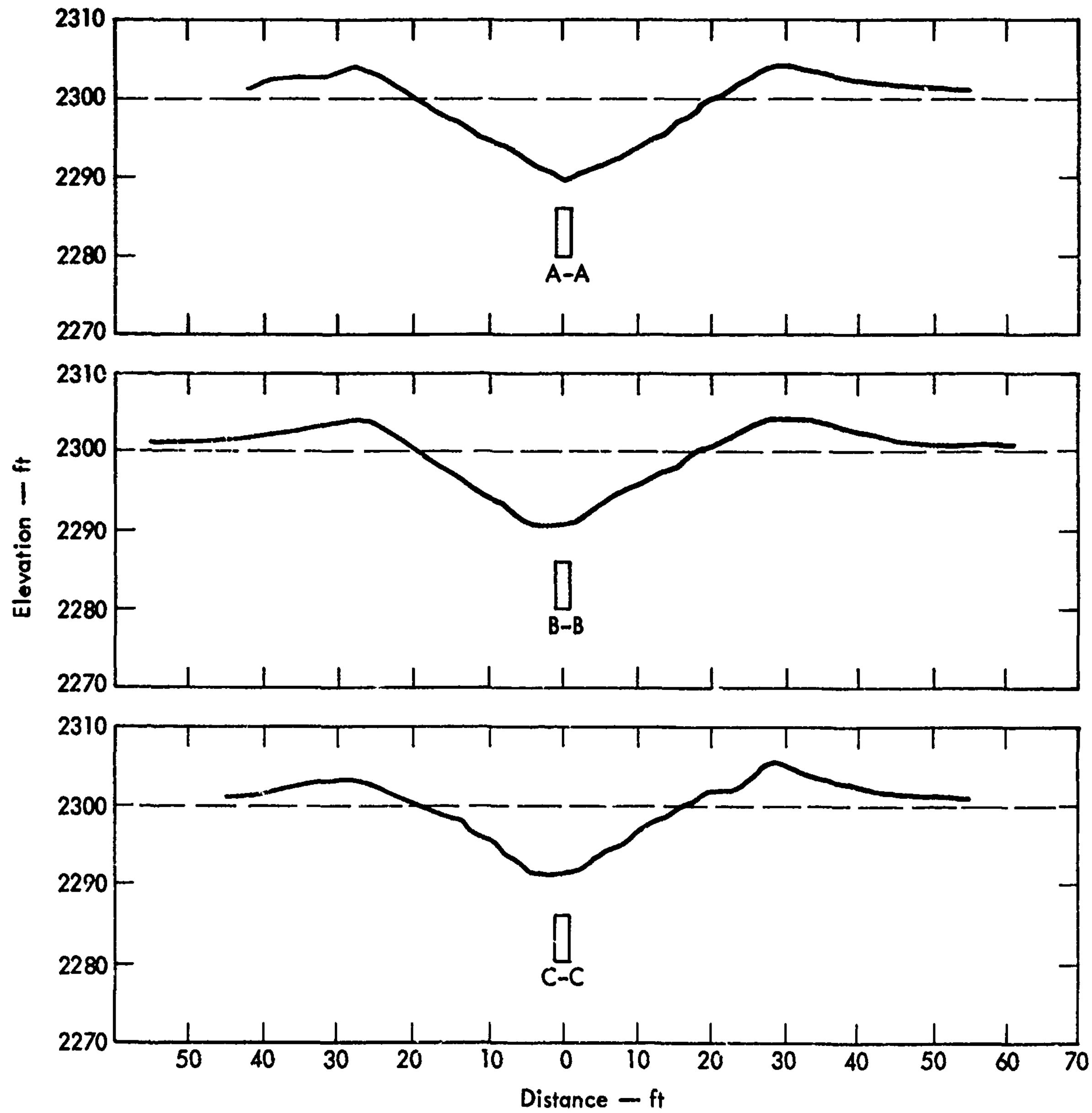


Fig. 30. PC-1 cross-sectional profiles.

transverse components of the peak particle velocity are shown in Appendix B. For additional details, Ref. 14 may be consulted.

Fig. 31. Oblique aerial view of PC-2 Crater. Note auto at right of photo (for scale).

MISSILE STUDY

The maximum missile range for the events in the PC and DRC series is presented in Table 9. Curves of the probability of missile impact for Series I and II are presented in Figs. 35 through 37. Detailed information on the technique used to form the missile probability is given in Ref. 15.

EXPLOSIVE PROPERTY VERIFICATION

The basic ingredients of the aluminized slurry evaluated throughout the A.O. II experiment consisted of aluminum capable of passing Minus 40 Mesh, U.S.

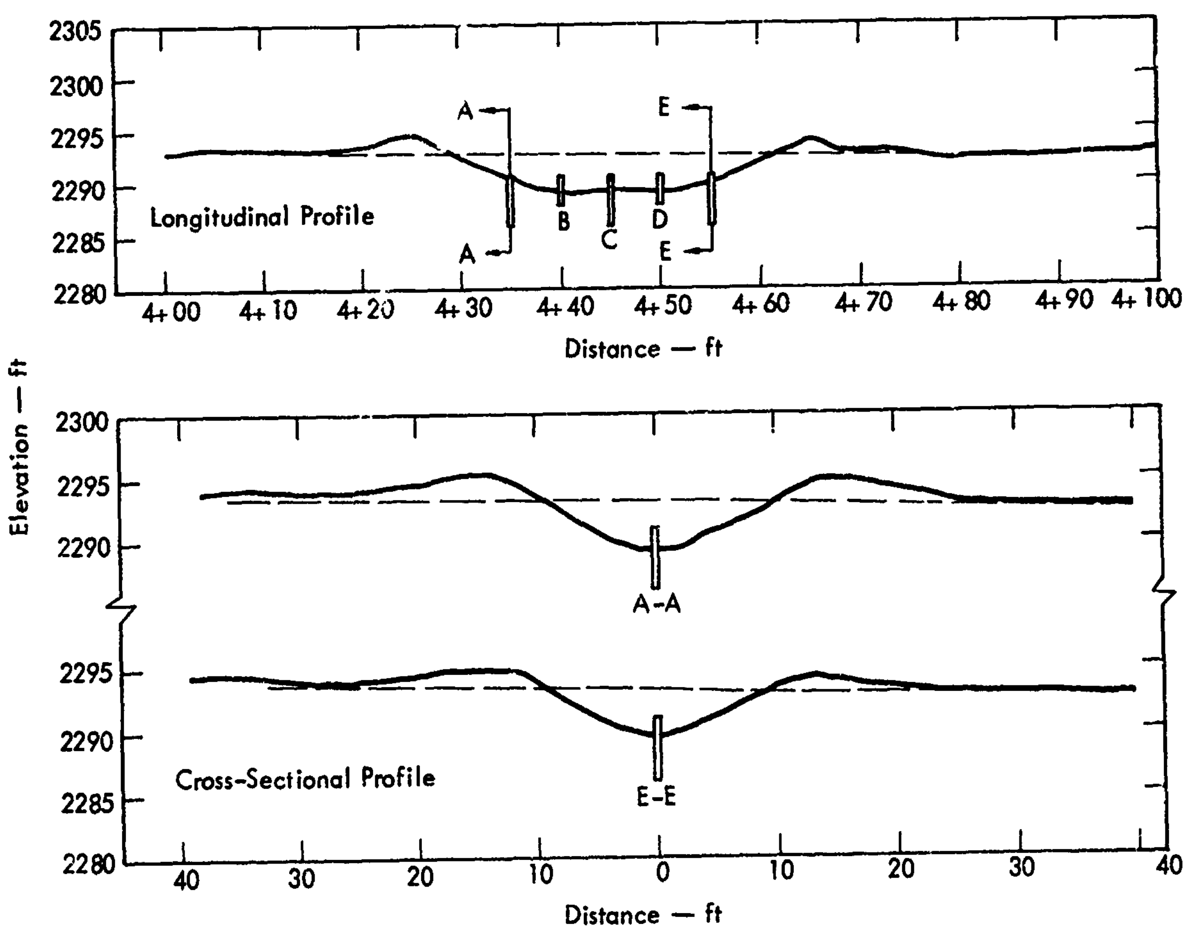


Fig. 32. DRC-1 longitudinal and cross-sectional profiles. (a) Longitudinal profile, (b) Cross-sectional profile.

Table 6. Armor Obstacle II, AN-ANFO Series crater measurements.

Total charge weight (lb)	40	40	55[a]
Explosive	AN	ANFO	H-6[b]
Method of emplacement	Canister	Special canister (similar to AN)	Shape charge and warhead
No. of emplacement holes	1	1	0
Dimension			
Apparent radius, R_a (ft)	6.5	6	2.5
Apparent depth, D_a (ft)	2.7	2.6	1.7
Lip height, H_{al} (ft)	1.3	0.8	1.3
Lip crest radius, R_{al} (ft)	8.5	7.5	8.5
Apparent volume, V_a (ft^3)	99	85	15

[a]15 lb shaped charges and 40-lb warhead (XM-180).

[b]H-6 Composition 45% RDX, 30% TNT, and 20% Al (XM-180).

Table 7. Summary of airblast overpressures for Armor Obstacle II Series.

Shot designation	Approximate distance from GZ to station (ft)	Predicted values (psi)	Maximum measured peak overpressures (psi)
PC-1	1,605	0.310	0.184
	5,413	.090	.035
	14,006	.040	.006
PC-2	1,517	.210	.177
	5,325	.054	.043
	13,260	.028	
PC-3[a]	1,434	.310	.168
	5,225	.090	.036
	13,870	.040	.037
DRC-1	815	.017	.094
	1,797	.0072	.045
	4,216	.003	.014
DRC-2	810	.017	.059
	1,700	.0072	.026
	4,215	.003	.0113
DRC-3	815	.012	.020
	1,792	.0052	.009
	4,216	.002	.004
DRC-4	737	.018	.065
	1,713	.0075	.032
	4,136	.003	.012
DRC-5	737	.012	.010
	1,713	.005	.004
	4,136	0.002	0.001

[a]Incomplete detonation; one of the three charges did not detonate.

Table 8. Ground motion peak particle velocities and predominant frequencies for the PC and DRC Series.[14]

Shot Designation	Seismic Station No.	Distance km	Vertical: Compression Wave PPV cm/sec	Vertical: Compression Wave Predominant Frequency Hz	Vertical: Rayleigh Wave PPV cm/sec	Vertical: Rayleigh Wave Predominant Frequency Hz	Radial: Compression Wave PPV cm/sec	Radial: Compression Wave Predominant Frequency Hz	Radial: Rayleigh Wave PPV cm/sec	Radial: Rayleigh Wave Predominant Frequency Hz	Transverse: Compression Wave PPV cm/sec	Transverse: Compression Wave Predominant Frequency Hz	Transverse: Rayleigh Wave PPV cm/sec	Transverse: Rayleigh Wave Predominant Frequency Hz
PC-1	3A	0.30	1.7000	30	1.8000	6	0.6500	25	2.1500	6	0.3500	25	1.9000	5
	4A	1.00	0.6200	29	0.4500	4	0.2100	33	0.4400	5	0.2100	29	0.2900	5
	5	2.60	0.1850	25	0.0550	3	0.0660	22	0.0970	5	0.0570	30	0.0530	3
	6B	4.20	0.0430	22	0.0480	3	0.0320	25	0.0650	3	0.0260	20	0.0370	3
PC-2	3A	0.30	1.1000	29	1.5000	5	0.4000	20	1.5500	7	0.2000	40	1.5000	5
	4A	1.00	0.3600	29	0.5800	5	0.1100	33	0.3800	5	0.0900	30	0.2300	5
	5	2.60	0.1300	22	0.0450	3	0.0500	14	0.0800	4	0.0350	29	0.0470	3
	6B	4.20	0.0380	20	0.0420	3	0.0250	25	0.0480	3	0.0210	20	0.0370	4
PC-3	3A	0.40	0.7000	25	1.1000	5	0.3000	22	0.8000	5	0.2000	29	0.8000	7
	4A	1.10	0.3000	25	0.4000	[illegible]	0.0900	29	0.2600	3	0.0800	29	0.2900	4
	5	2.70	0.1300	22	0.0700	3	0.0450	17	0.0750	5	0.0350	29	0.0450	3
	6B	4.20	0.0520	25	0.0420	2	0.0250	25	0.0580	2	0.0220	20	0.0240	3
DRC-1	2	0.10	1.8000	26	2.0000	8	1.4000	25	2.6000	10	0.5000	25	0.7000	10
	3A	0.36	0.1100	25	0.4500	8	0.0500	20	0.3200	8	0.0500	25	0.2600	7
	4A	1.00	0.0400	27	0.0700	5	0.0120	33	0.0410	7	0.0100	30	0.0390	4
	5	2.70	0.0210	34	0.0050	5	0.0050	33	0.0050	5	0.0040	40	0.0040	5
DRC-2	2	0.09	1.1000	29	1.4000	20	0.6000	29	1.6500	9	0.3000	50	0.9500	9
	3A	0.36	0.0700	29	0.3200	8	0.0400	25	0.2100	8	0.0300	25	0.2300	7
	4A	1.00	0.0220	29	0.0200	5	0.0080	32	0.0260	7	0.0060	29	0.0220	6
	5	2.70	0.0150	36	0.0040	3	0.0040	36	0.0040	5	0.0030	36	0.0020	5
DRC-3	2	0.10	1.1000	25	1.7000	9	0.4000	29	1.5000	11	0.4000	22	1.2000	10
	3A	0.36	0.0800	20	0.4800	7	0.0500	25	0.2800	8	0.0400	25	0.2000	7
	4A	1.00	0.0280	28	0.0560	4	0.0100	32	0.0470	6	0.0080	25	0.0280	5
	5	2.70	0.0150	36	0.0030	3	0.0040	34	0.0040	4	0.0030	34	0.0030	5
DRC-4	2	0.12	1.1000	29	1.5000	8	0.3000	27	1.7000	14	0.1500	28	0.8000	14
	3A	0.38	0.0800	22	0.3400	8	0.0350	22	0.2700	7	0.0300	22	0.1500	8
	4A	1.10	0.0340	29	0.0490	4	0.0100	33	0.0320	5	0.0080	29	0.0300	5
	5	2.70	0.0210	33	0.0050	5	0.0060	31	0.0050	6	0.0050	34	0.0030	4
DRC-5	2	0.12	0.3000	25	0.8000	8	0.1000	29	0.5000	8	0.0500	25	0.5000	11
	3A	0.38	0.0350	18	0.2100	7	0.0200	20	0.1500	8	0.0150	25	0.0600	8
	4A	1.10	0.0100	25	0.0180	4	0.0050	30	0.0250	6	0.0020	26	0.0120	5
	5	2.70	0.0050	32	0.0010	5	0.0010	28	0.0020	6	0.0010	33	0.0010	5

Series, and ammonium and sodium nitrate that served as the oxidizing agent. The remainder of the ingredients were water, organic solvents and gelling and stabilizing agents.

The explosive properties of the slurry as prescribed in the specifications by EERL and as reported by Dow are shown in Table 10. In addition to the listed properties, it was specified that the slurry would not be detonated by a Number 8 blasting cap, flame, or 220 Swift bullet impact.[16]

Results of the detonation velocity test conducted by the LLL Chemistry Department at Fort Peck are presented in Table 11. The average detonation velocity was 5030 meters/sec.

Table 9. Armor Obstacle II Series maximum missile range.

Event	Maximum missile range (ft)
PC-1	724
PC-2	541
DRC-1	658
DRC-2	443
DRC-3	405
DRC-4	517
DRC-5	434

Fig. 33. Oblique aerial view of several DRC and AN-ANFO craters.

Table 10. Explosive properties of Armor Obstacle II slurry.

Property	Specified by EERL	Reported by Dow
Density	1.25-1.35 g/cm^3	1.33 g/cm^3 at 18°C
Confined detonation velocity	4000-4800 m/sec	4660 m/sec at 10°C
Detonation pressure	Not specified	17.95 ± 1.41 kbar at 18°C
Total energy	800 cal/g	812 ± 31 cal/g at 18°C
Aluminum content	5%	10%

Table 11. Detonation velocity test of Armor Obstacle II slurry.

Pin No.	ΔD (mm)	Distance from booster (mm)	ΔT (sec)	Detonation velocity (m/sec)
1-2	50.3	650.3	9.8	5,400
2-3	49.2	709.5	9.9	4 900
3-4	51.1	760.6	11.3	4,500
4-5	49.6	810.2	9.4	5,250
5-6	47.3	857.5	9.6	4,920

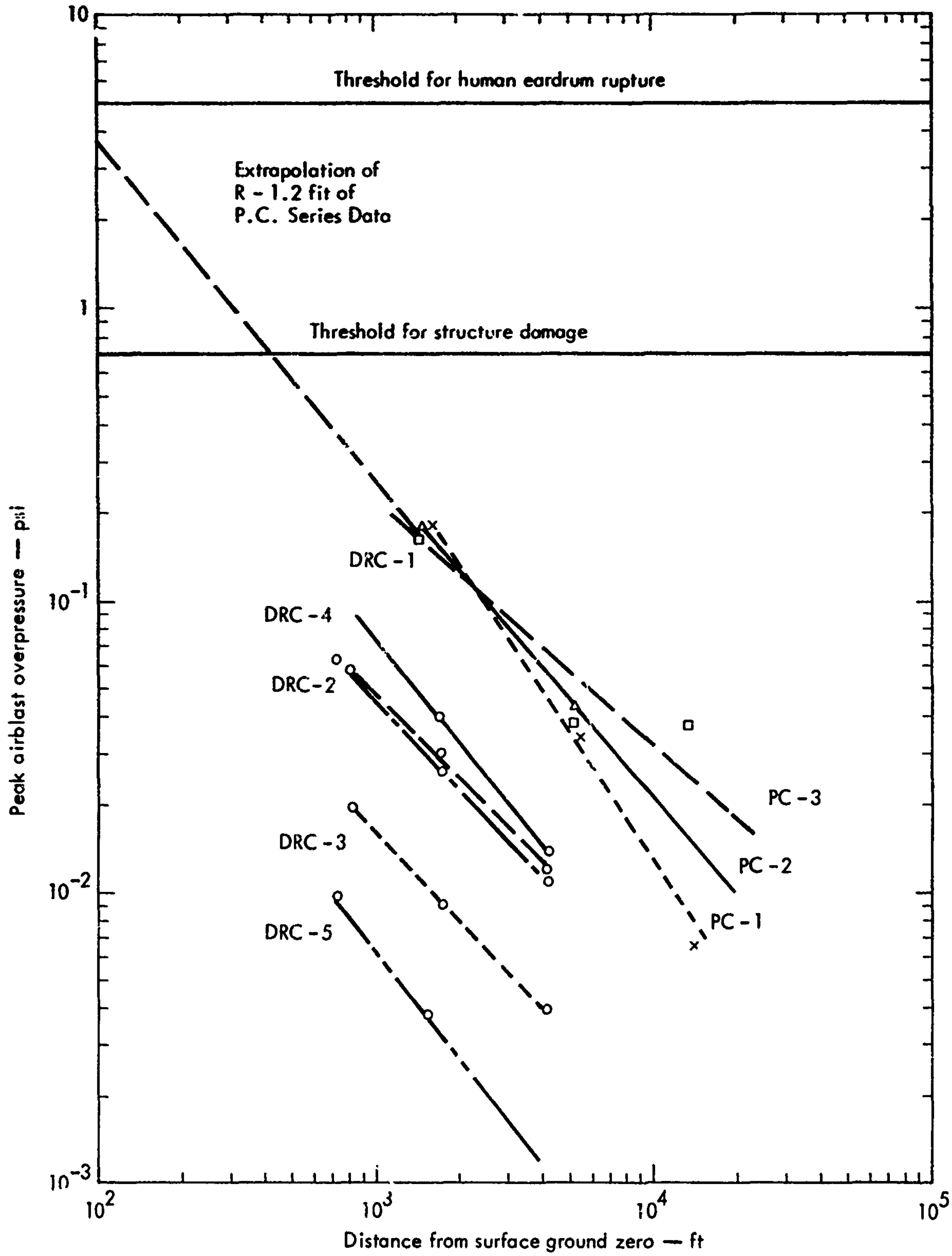


Fig. 34. Peak airblast overpressures as a function of range.

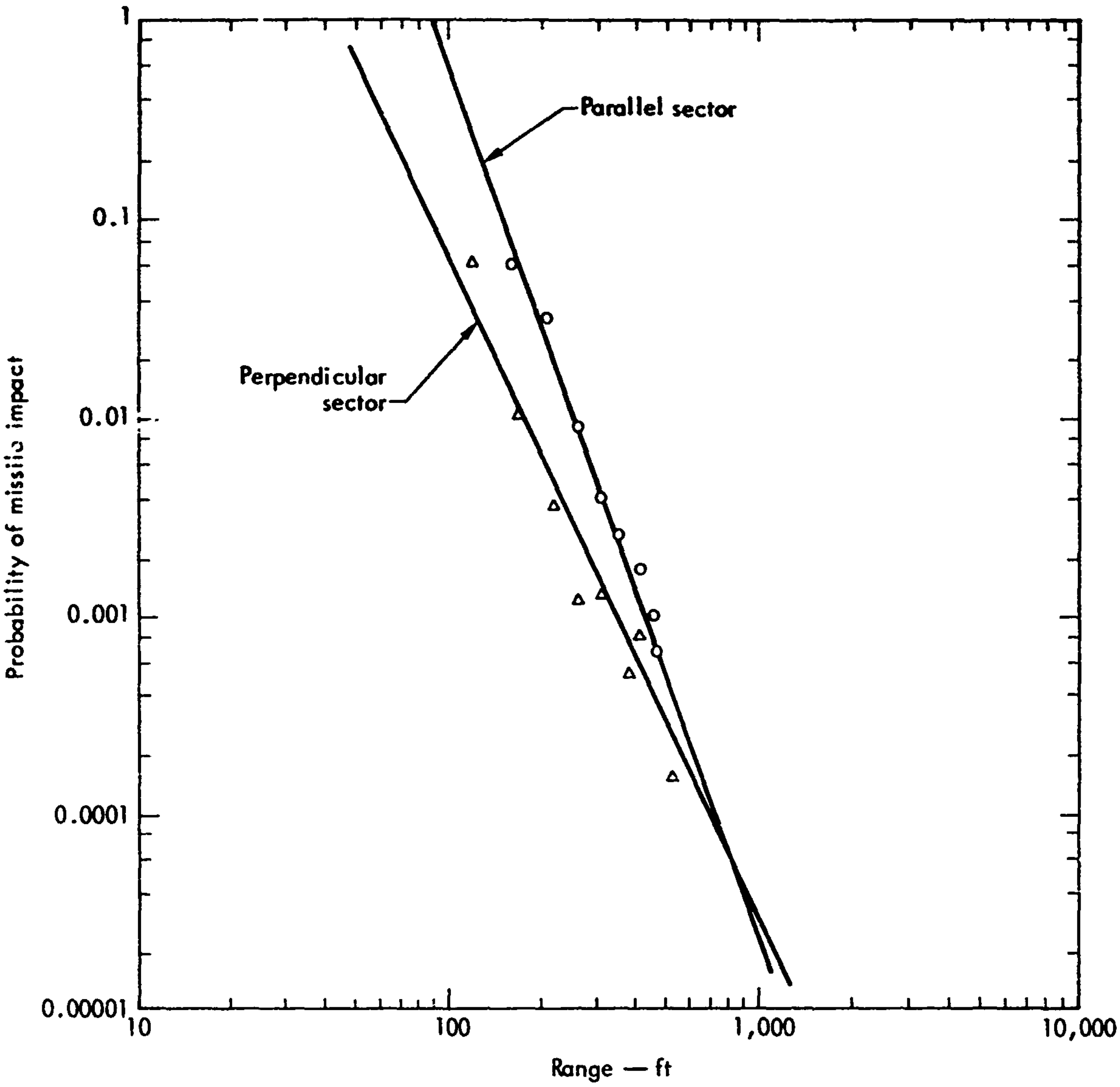


Fig. 35. Probability curve for missile impact, PC Series.

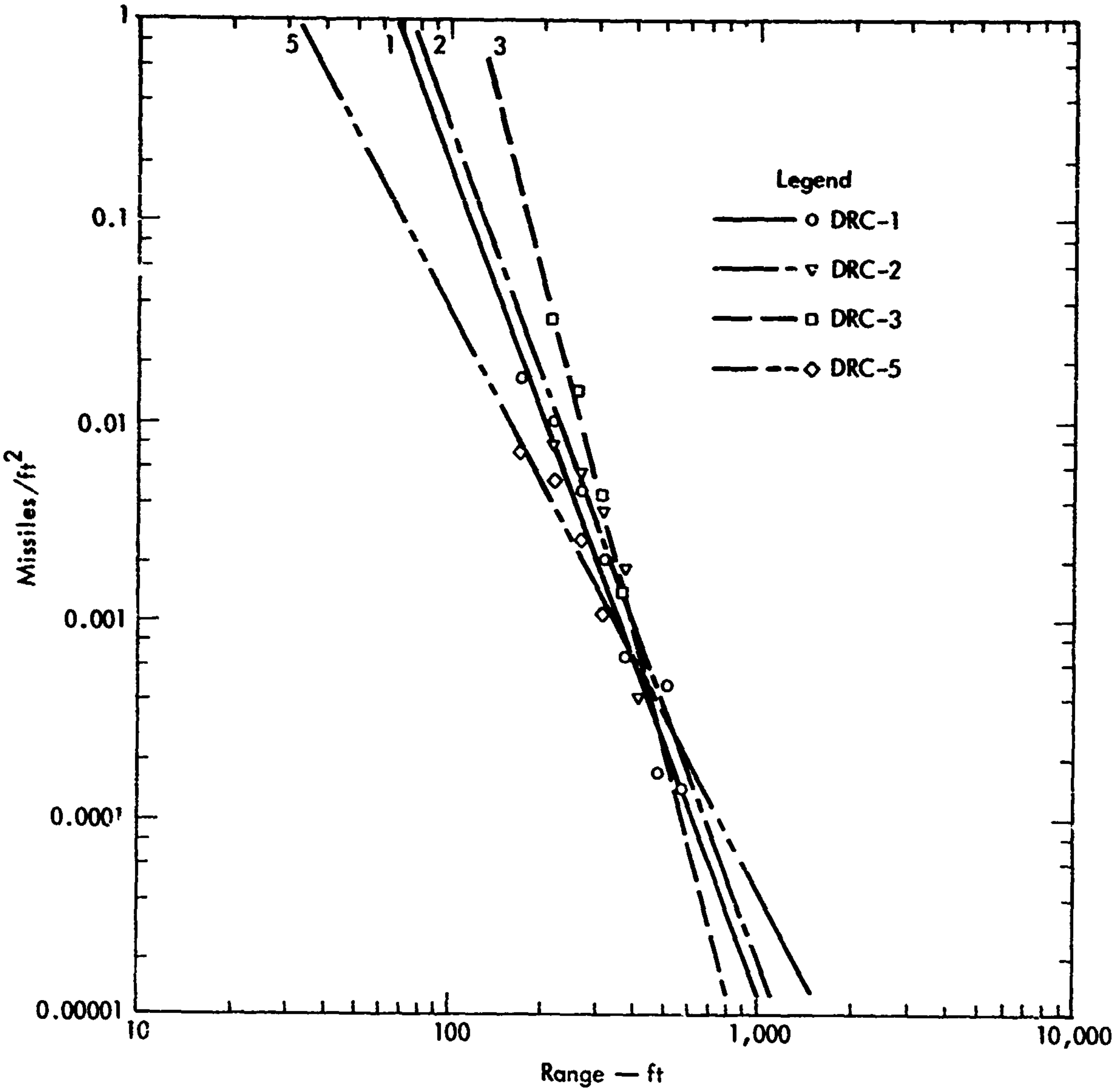


Fig. 36. Probability curve for missile impact, DRC Series (parallel sector).

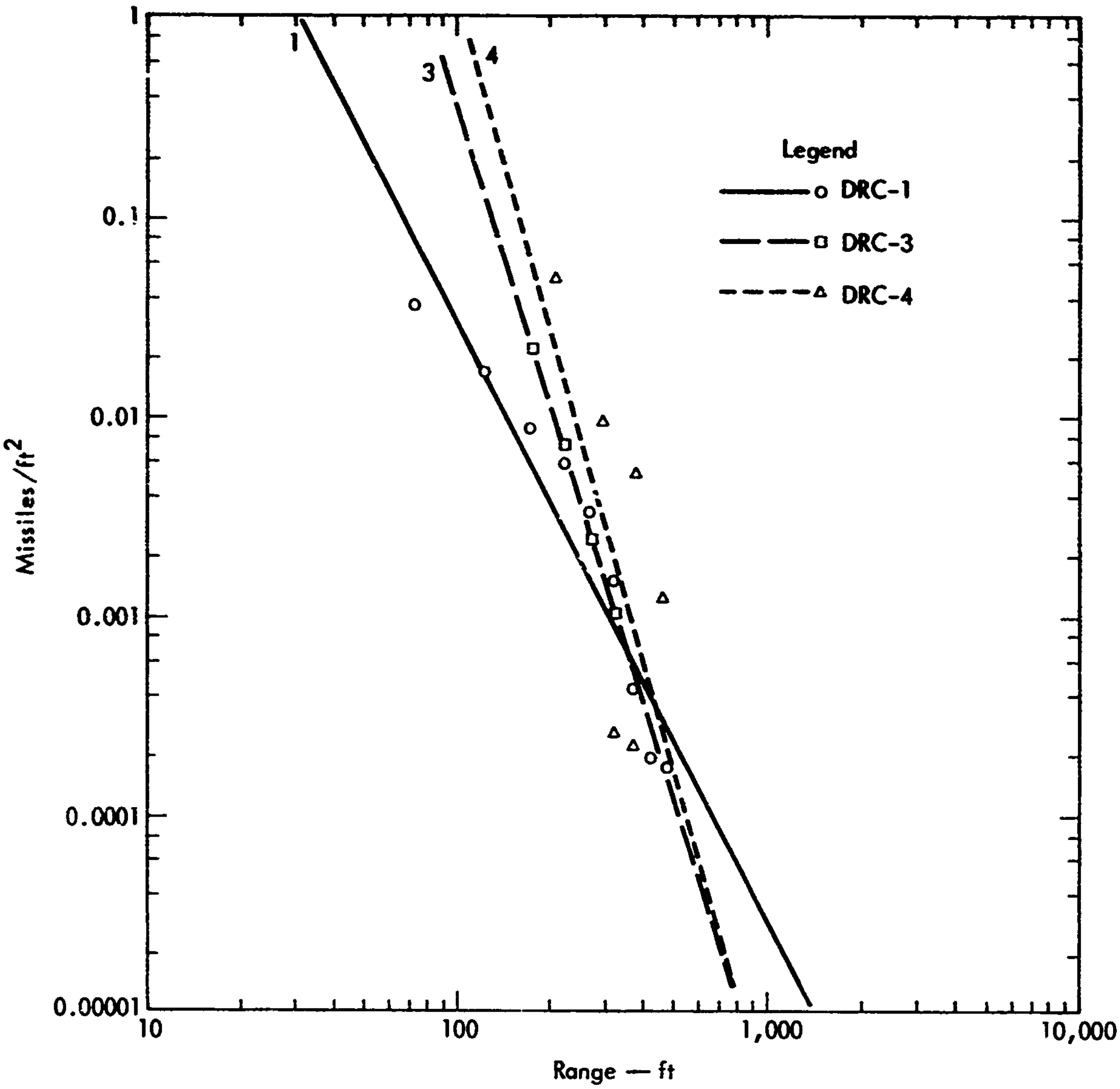


Fig. 37. Probability curve for missile impact, DRC Series (perpendicular sector).

TECHNICAL PHOTOGRAPHY

More than 400 black and white and color prints and slides were taken covering the major phases of each of the cratering and obstacle effectiveness studies in Project A.O. II. In addition, the detonation sequence for each of the PC and DRC detonations was documented with high-speed coverage. The usable footage obtained with the 16 mm camera was sufficient enough for EERL to produce a 15-min documentary film on the entire A.O. II field program for 1972.

OBSTACLE EFFECTIVENESS TEST

The majority of the craters produced in the PC and DRC series were tested to determine their obstacle effectiveness. Limited access to some of the tactical vehicles, several mechanical difficulties and structural damage inflicted on a few of the craters during recovery procedures, prevented all of the craters from being evaluated. Table 12 presents the crater dimensions for the seven 1-ton craters (IT) produced for the D.C. IIB Project.[3]

Initially, the entire mobility test and evaluation centered around the services of the 4-man crew and M-60 tank obtained from Fort Carson, Colorado. Because of major mechanical difficulties with the M-60 tank an urgent request was made to the National Guard element C Troop, in Glasgow, Montana, for the use of their M-48 tank. Because of the excellent training afforded by this opportunity, C Troop volunteered to subject their Armored Personnel Carrier and a representative sample of their other tactical vehicles to the same test. Results of the obstacle effectiveness test are presented in Tables 13, 14, and 15.

The main battle tanks were the only vehicles evaluated in the PC craters. Figure 38 illustrates the M-60 tank successfully exiting PC-1. The APC and 2-1/2 ton truck were not able to exit the DRC craters as shown in Figs. 39 and 40. The 1/4- and 2-1/2-ton trucks experienced the same difficulty attempting to

Table 12. Diamond Ore IIB preliminary crater dimensions.[3]

Dimension[a]	IT-1	IT-2	IT-3	IT-4	IT-5	IT-6	6 meters
Yield (tons of nitromethane)	1-ton	1-ton	1-ton	1-ton	1-ton	1-ton[b]	17 tons
DOB	5	10	15	20	25	18	20 (6 meters)
Apparent radius (R_a)	19.3	23.4	23.3	23.1	20.0	23.6	70.0
Apparent depth (D_a)	10.5	16.0	13.2	10.0	8.0	12.1	34.0
Lip height (H_{al})	1.5	3.0	3.5	4.3	5.8	2.8	9.6
Lip crest radius (R_{al})	22.9	29.4	28.1	31.2	32.6	29.4	83.5
Apparent volume	4,391.5	10,032.4	8,373.6	7,082.0	4,347.0	8,609.5	215,641.1
Maximum missile range	1,025	1,033	879	785	820	867	2,733

[a]All lengths are in feet and all volumes are in ft^3.

[b]Gelled nitromethane (by weight, 87% nitromethane, 10% trace sand, 3% gelling agent).

Table 13. Obstacle effectiveness for PC Series 1 and 2 and DRC Series 1, 2, and 3.

Crater	Vehicles	No. of attempts A	B	C	Time in crater A	B	C	Remarks
PC-1 (TNT)	M-60	6	15	3	2 min	4 min	1.5 min	No major problems
	M-48	1	2	1	15 sec	1 min	15 sec	Same line as M-60
PC-2 (slurry)	M-60	2	2	3	30 sec	30 sec	1.5 min	On 3rd attempt in Hole C, a track was thrown. Dozer and M-48 worked for 1 hr and 15 min before pulling the M-60 out.
	M-48							Not evaluated because crater was destroyed attempting to rescue the M-60.
DRC-1	APC		5			4 min		Nosed into fwd crater slope. Could not move material easily. Unable to exit. Possible transmission problems.
	1/4 jeep (M38A1)		10			3 min		Had to rock excessively and grounded at top of enemy side of crater.
	M-60		1			30 sec		No problems.
DRC-2	APC		1			30 sec		
	2-1/2 truck		3			45 sec		Dug nose into enemy side of crater.
	1/4 jeep (M151A1)		4			2 min		
	1/4 jeep (M38A1)		9			4 min		Wore down the exit slope composed of weathered material.
DRC-3	APC		4			3.5 min		Nosed into enemy side of crater and pushed its way out.
	2-1/2 truck		10			5 min		Bumper dug out enemy side of crater.
	1/4 jeep (M151A1)		5			2.5 min		4-wheel drive
	1/4 jeep (M38A1)		1			30 sec		4-wheel drive

NOTE: M-60 moved through DRC-1 on the first attempt without difficulty. No subsequent trials on the other DRC's were conducted.

negotiate one of the D.O. IIB 1-ton craters (Fig. 41).

The largest crater evaluated in this series resulted from the detonation of 17 tons of nitromethane for Project D.O. IIB (Table 12). Neither of the two tanks came close to exiting this particular crater under its own power. Even after the construction of the exit channel, which proved to be a major construction task, the tanks had to make several attempts before successfully exiting. Figures 42-44 illustrate the extent of the work required to remove the M-60 from this crater and of the mechanical effort to create an exit channel that enabled the tanks to exit the crater unassisted.

The attempt to create an expedient exit in the lip of the 6-M crater resulted in an opening that was 7 ft deep and 20 ft wide. Figure 45 shows the M-60 attempting to reach the expedient opening after

Table 14. Obstacle effectiveness results for Diamond Ore IIB 1-ton series (IT 1-6).

Crater	Vehicles	No. of attempts	Time in crater	Remarks
IT-1 (OLr)[a]—24.9 (ODa)[b]—12.3	M-60	8	5 min	No major problems
	M-48	5	5 min	No major problems
	APC-M59	1	30 sec	Followed tank trail
IT-2 (OLr)—31.3 (ODa)—17.6	M-60	5	5 min	Tank appeared to have transmission problems; unable to climb slopes.
	M-60	6	4 min	Dozer spent 35 min building exit ramp
IT-3 (OLr)—29.8 (ODa)—17.0	M-48	14	12 min	Started to throw track; was pulled from crater by dozer
	M-60	5	4 min	Crossed $\vert$ to M-48; no problems
IT-4 (OLr)—32.2 (ODa)—13.5	M-48	11	5 min	Movement was $\vert$ to M-60 crossing
	M-60	10	4 min	Movement was $\vert$ to M-48 crossing
IT-5 (OLr)—33.8 (ODa)—14.3	M-48	15	10 min	No major problems
	M-60	6	3 min	Crossed $\vert$ to M-48
IT-6 (OLr)—32.8 (ODa)—13.8	M-60	21	10 min	
	M-48	1	30 sec	Followed the M-60 trail

[a]OLr—obstacle lip radius.

[b]ODa—obstacle depth of crater.

Table 15. Obstacle effectiveness results for Diamond Ore IIB 17-ton shot (6-meter DOB).

Crater	Vehicle	No. of attempts	Time in crater (min)	Remarks
6 meter	M-48	19	9	Forward progress ~24 ft up enemy side.
	M-48	3	2	Second trial, on different line of action. Forward progress: ~32 ft.
	M-48	—	12	Attempt to spiral out was unsucessful; threw track.
	M-48	5	7	After pulling tank out, dozer spent 2 hr and 15 min preparing an exit ramp through the crater.
	M-60	18	7	Forward progress ~20 ft up enemy side, $\vert$ to M-48 attempt.
	M 48	10	4	Forward progress ~22 ft up enemy side in same path of M-60.
	M-60	7	2	Using exit ramp constructed for the M-48.

crossing the exit ramp constructed by the bulldozer. A summary of the observations recorded during the obstacle effectiveness study, made by an officer from the U.S. Army Armor School, is presented in Appendix C.

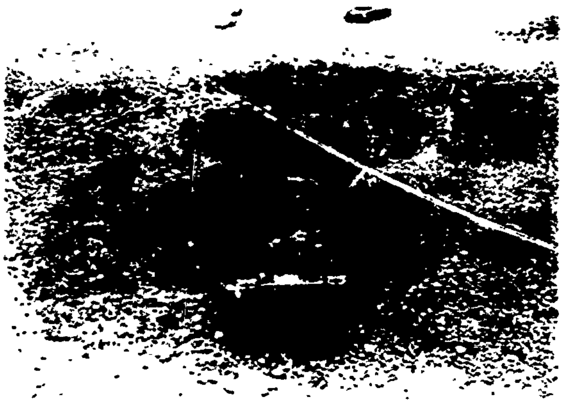


Fig. 38. M-60 Tank successfully exiting PC-1 Crater.

Fig. 39. Armored personnel carrier unable to exit DRC-5 Crater.

Fig. 40. Extended bumper on 2-1/2 ton truck creates problems in exiting DRC-2 Crater.

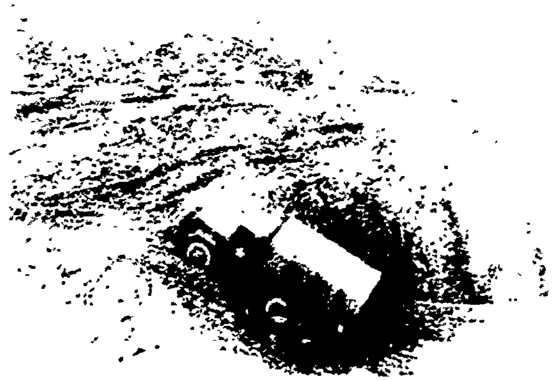


Fig. 41. 2-1/2 ton truck having difficulty exiting IT-3 Crater with exit ramp.

Fig. 42. M-48 Tank and bulldozer required to remove M-60 Tank from D.O. IIB 6 meter Crater.

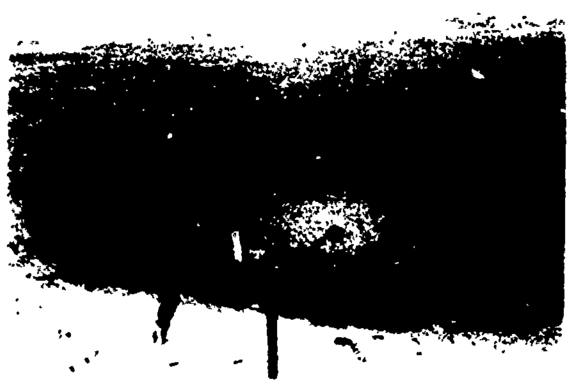


Fig. 43. Bulldozer constructing exit in D.O. IIB 6 meter Crater.

Fig. 44. M-60 Tank making several attempts to exit D.O. IIB Crater with exit ramp.

Fig. 45. M-60 Tank attempting to reach expedient opening in lip of D.O. IIB 6 meter Crater.

Chapter 4. Analysis

In this chapter, the experimental procedures employed and test results obtained during the four phases of Project A.O. II are analyzed with respect to the technical objectives listed in Chapter 1.

A major assumption which dictated the direction of the three phases of Project A.O. II was the relative cratering effectiveness associated with a 10% aluminized slurry as reported in Ref. 1. In terms of excavated volume, the slurry used for the overall program was expected to be between 20 and 30% more effective than the TNT and ammonium nitrate. This expectation was based upon a series of small-scale cratering effectiveness tests conducted in sand at EERL's model test facility. The craters produced in both the PC and DRC series failed to verify EERL's cratering effectiveness values.

PRECHAMBERED HOLES (PC SERIES)

Contrary to predictions, the PC-1 crater created by 3960 lb of TNT was a larger crater than PC-2 which was produced by 3000 lb of slurry. The identical emplacement configurations for these two craters are shown in Figs. 4 and 8. Current doctrine calls for the employment of the prechambered holes at 45.7-ft spacings. This spacing is not designed to provide a smooth row crater, but to try to optimize obstacle effectiveness.

Although there is an average difference of 5-1/2 ft in the radius of the apparent crater, R_a (see Table 9), there is only an average difference of 3-1/2 ft in radius at the crater lip, R_{al}, which is significant in terms of obstacle effectiveness. In terms of excavated volume, the material ejected from PC-2, was only 41% of the quantity removed from PC-1. The third charge of the PC-3 crater, which consisted of 1320 lb of nitromethane, failed to detonate simultaneously with the first and second charges, as confirmed by Fig. 46. The resulting crater dimensions of the two charges that did fire simultaneously were similar in all dimensions to the PC-1 holes, as shown in Table 3 and Fig. D-1.

The failure of one of the nitromethane shots to detonate was probably due to the boosting method used. Since this was an add-on shot, materials were not available to fabricate boosters. Instead 1 to 2 lb of Composition C4 was molded in plastic bags and taped to the side of each drum. These were initiated with detonating cord. The problem arises from the fact that the drums used to ship and store nitromethane have a low bursting pressure. Due to the placement of the booster, it could rupture the drum before the nitromethane detonated.

Redrilling of the unblasted hole to the depth of the top drum revealed little evidence of what had occurred. Another 55-gallon drum of nitromethane was placed in the hole and boosted in the same manner. The booster failed to detonate the nitromethane, blowing the top of the burst drum out of the hole. Originally there was some question as to whether cutoff occurred to the detonating cord downlines. High-speed photography, however, did not verify this hypothesis.

Fig. 46. PC-3 detonation.

Al SLURRY VS 40-LB AN CRATERING CHARGE (DRC DESIGN)

The basic difference in the design for the Deliberate Road Craters 1, 2, and 3 illustrated in Figs. 16, 17, and 18 lies in the amount, type, and method of employment of the explosive. Although DRC-1 and 2 called for the same weight of explosive, the Army's standard 40-lb ammonium nitrate canisters were used for DRC-1, and 40-lb bags of slurry were used for DRC-2. Slurry explosives were also employed in DRC-3 but, in this case, the quantity of explosive per hole was reduced, assuming a relative effectiveness factor of 1.3, and the slurry was removed from the bags and poured into the emplacement holes. DRC-1, the Army's standard design, produced the largest crater in terms of crater dimensions and excavated volume. The volume of material removed from DRC-2 was 40% less than DRC-1 (see Table 5). It is evident from Table 5 and Fig. D-2 that even though DRC-3 used only 240 lb of explosive, compared to the 320 lb employed in DRC-1 and 2, it produced a crater equal in dimensions to DRC-2. Once again this particular slurry failed to exhibit its assumed relative effectiveness. The similar dimensions of DRC-2 and 3, in spite of different quantities of slurry, may be attributed to the fact that the slurry was poured into the emplacement holes, providing excellent coupling with the media.

MODIFICATION OF DRC DESIGN

The standard DRC design was modified in the DRC-4 and DRC-5 detonations in order to exploit the assumed greater crater effectiveness of slurry explosives compared to ammonium nitrate (see

Figs. 19 and 20). The results of the DRC-4 and DRC-5 detonations were very encouraging. Although the DRC-4 design called for an additional 40-lb bag of the selected slurry to produce crater dimensions similar to those anticipated for the DRC-1 design, the shot was done with two fewer emplacement holes (Table 5 and Fig. D-3). On the other hand, the modified DRC-5 using 80 lb less explosive than the standard DRC-2 and only three emplacement holes produced a crater similar in dimension, though of smaller volume. Based on the comparison between bagged and poured slurry (DRC-2 and DRC-3), it is reasonable to assume that the performance of DRC-5 with three holes and poured (rather than bagged) would have outperformed DRC-3 with five holes and poured slurry (Table 5 and Figs. D-4).

AMMONIUM NITRATE CRATERING CHARGE VS PRILLED AMMONIUM NITRATE AND FUEL OIL (ANFO)

Single detonations were designed to evaluate the effectiveness of ANFO for cratering in a clay shale as shown in Fig. 23. To overcome the hydroscopic properties of ANFO, a canister similar in dimension to the Army's standard AN canister was fabricated to hold the ANFO. Results of the ANFO detonation confirmed that the cratering ability of ANFO was comparable to the mixture of ammonium nitrate and TNT contained in the Army's 40-lb cratering charge as shown in Table 5 and Fig. D-5.

CRATERING EFFECTIVENESS OF XM-180

In addition to the rapid explosive excavation techniques evaluated in the DRC

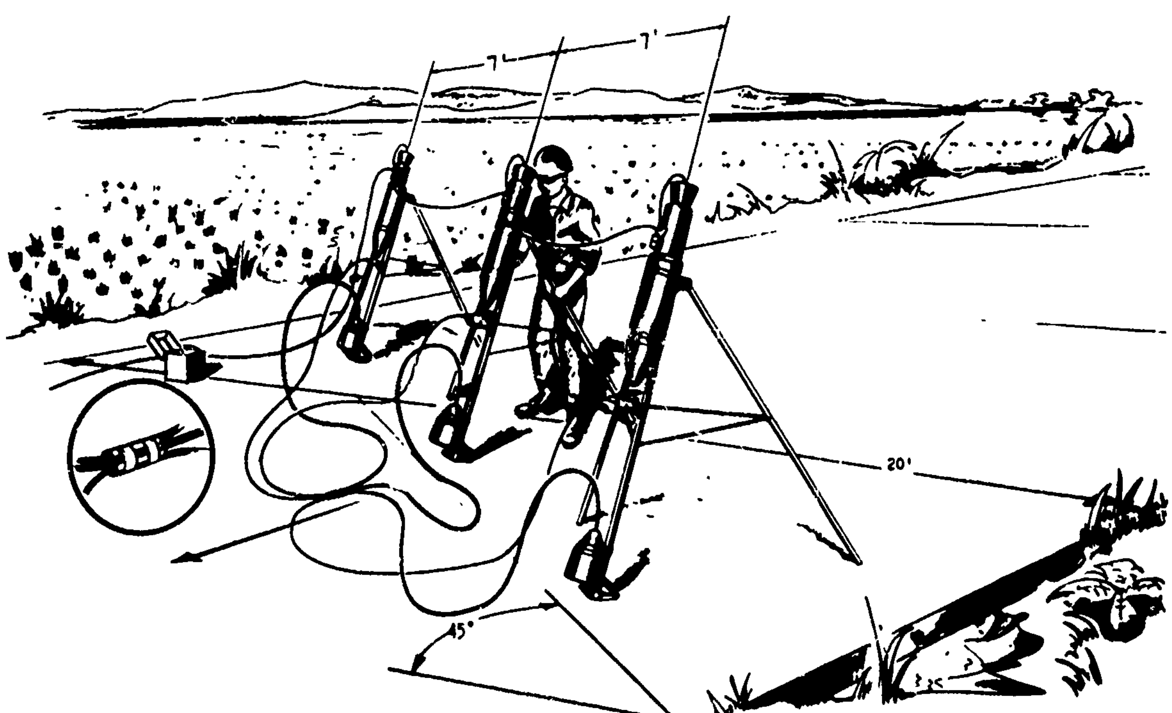


Fig. 47. Configuration for the employment of XM-180 Cratering Kit.

seric   Demolition Kit Cratering XM-180 (Fig. 25), was tested. The kit, which has a maximum 15-min set-up time for two men, is light, easy to handle, and designed to produce craters in roadways that are obstacles for both tracked or wheeled vehicles. Under normal conditions it is designed to be used in groups of three or five as shown in Fig. 47. The results of previous experimental detonations of single kits in a sandy clay have produced craters which averaged 7 ft in depth and about 21 ft in diameter. Reference to Table 6 and Fig. A-16 will show that the 3-ft deep, 17-ft diam crater (lip diameter) produced in the Fort Peck clay shale was less than anticipated compared to the results that were obtained at Aberdeen Proving Ground.[10] The XM-180 is still in the experimental stage and is presently undergoing further evaluation by the Army Material Command.

Fig. 48. German DM 41A1 "Cheesecake" Charge.

EXPLOSIVE CONTAINERS AND HANDLING REQUIREMENTS

Prechambered Holes

The attempt to evaluate the handling requirements and problems associated with loading the PC chambers was hindered by the explosive manufacturer's failure to cast the TNT cylinders with handles on their sides. The charges as received had small loops located near the center of the cylinder which were too small to be useful. Figure 48 shows the German DM 41A1 "Cheesecake" charge. Instead of loading the TNT cylinders individually with the emplacement poles as pictured in Fig. 49, a special cage was fabricated that enabled the TNT cylinders to be loaded into the cages completely above ground. Before loading the TNT charges, the small string loops had to be removed to ensure adequate contact between charges as shown in Fig. 50. A drill rig was used to lower the cages into the three holes. The loading times and equipment associated with this loading operation are not representative of the time and equipment which would normally be required.

Loading of the slurry into the PC holes was a relatively simple operation. Initially, the slurry was off-loaded next to each of the three holes in the boxes which contained a 40-lb bag of slurry. Two of the three holes were loaded by lowering several bags with a nylon cord to the bottom of the chamber to act as a cushion for the remaining bags which were subsequently dropped in, as described in Chapter 2. The loading time by two men per hole was 10 min. The need to recover the explosive from these two holes was considered unlikely, so individual cords, lines, etc., for each bag were not secured at the top of the chamber.

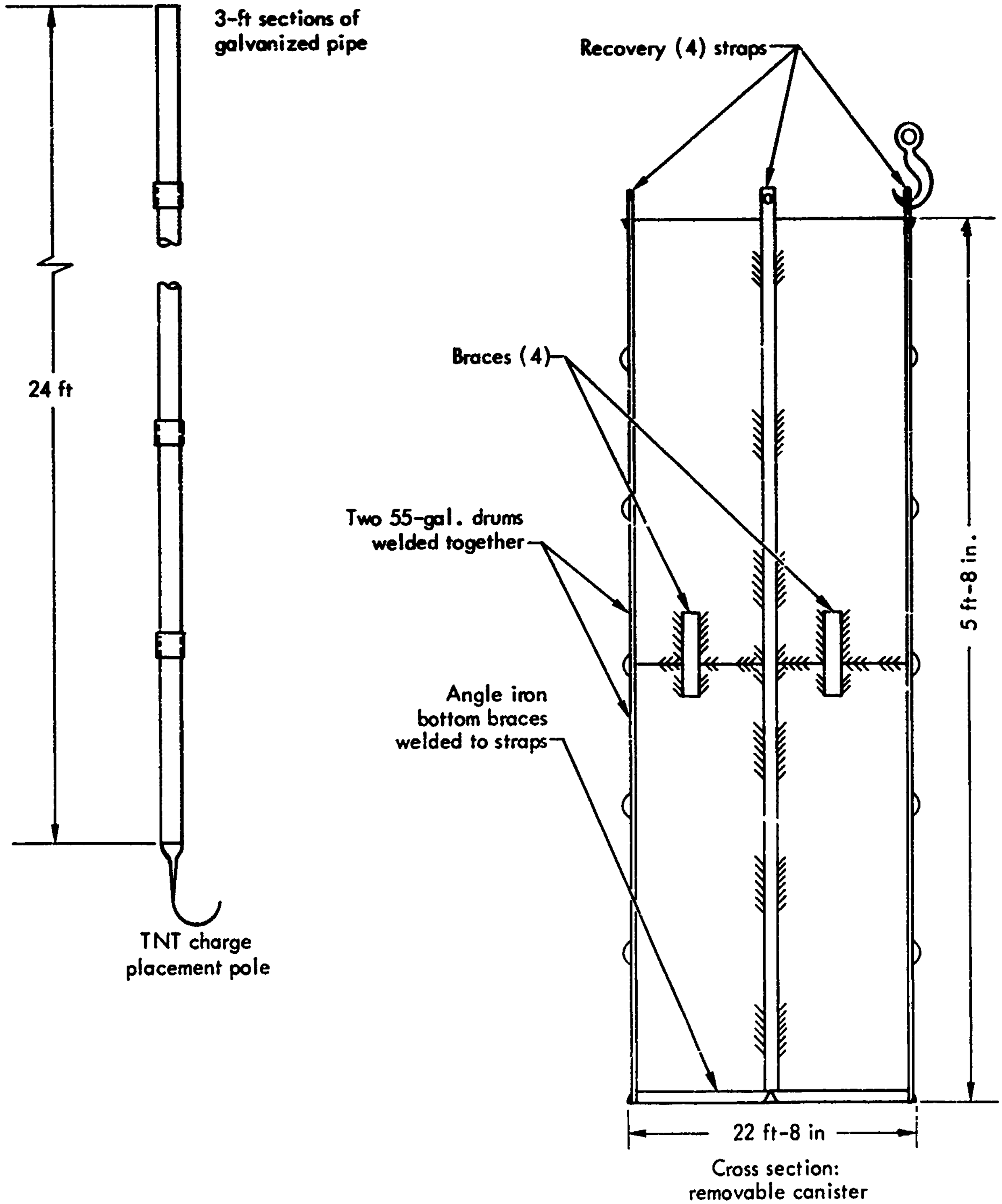


Fig. 49. Recoverable explosive canister and poles.

The third hole of PC-2 was used to evaluate a technique for recovering the explosive in case of a cancelled mission. Originally a container consisting of two 55-gallon drums welded together (Fig. 49) was designed to emplace and unload the slurry charge for PC-2A. But the fabricated container turned out to be too large to insert into the concrete culvert lining the chamber. Since corrugated culvert

Fig. 50. Removal of string loop from TNT charges.

material is readily available to the average engineer battalion, an expedient 18-in. diam corrugated culvert was fabricated to replace the 55-gallon drum container. The container was put together with a circular wooden bottom and a 1/2-in. steel cable across the top for lifting and lowering the charge. Emplacing the slurry-loaded culvert pipe into the prechambered hole was also a simple operation. Preemplacement of recovery canisters for the use of slurry explosive in the PC holes would prevent the loading time from exceeding 10 min per hole.

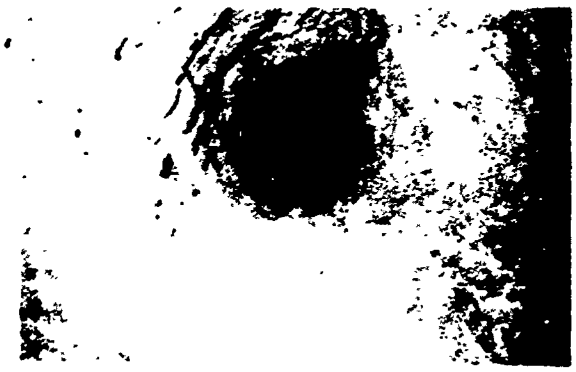
Instead of attempting to lower the 55-gallon drums of nitromethane into the PC-3 holes and taking the chance of dropping one, empty drums were lowered into the chambers one at a time with a C-4 booster taped to their sides. A rubber hose was placed in a hole at the top of each empty drum to feed the nitromethane from the storage drums into the downhole drum. Despite the excellent cratering results compared to PC-1 as shown in Table 3 and Fig. 33, the failure of one of the three nitromethane charges to fire as well as the excessive loading time associated with the loading technique detract from the attractiveness of employing nitromethane in prechambered holes.

Differences in the size and shapes of the loading containers employed in the three PC detonations apparently made no significant contribution to the resulting crater dimensions.

Deliberate Road Craters

Shaped charges were used to make the emplacement holes for most of the deliberate road craters. The shaped charges were fired from a 12-in. standoff and had an average effective penetration depth of 60 in. Removal of the fractured material from the emplacement holes for both the standard and slurry DRC's was the time-consuming portion of each loading operation. The standard posthole digger and hand auger were not long enough to clean out the 7-ft emplacement holes. Therefore, it was necessary to add an extension to the hand auger. The actual loading of the ammonium nitrate canisters and the slurry bags was a quick and simple operation. An additional 3 min per hole were required to prepare and place the 1-lb precast boosters in the bags of slurry for those designs that required bagged charges. If the boosters were prepared while the emplacement holes were being constructed, the 3-min booster preparation requirement could be cut in half. Removing the slurry from the bags and pouring it into the emplacement holes for DRC-3 added no significant time requirement to the operation. The effectiveness of pouring the explosive and completely filling all of the voids in the emplacement hole is illustrated in the bottom half of Fig. 51.

(a)



(b)

Fig. 51. (a) 40-lb AN Canister and (b) 40 lb of slurry in a DRC emplacement.

EXPLOSIVE PROPERTIES

Although the slurry explosive provided by the manufacturer was within the range of explosive properties specified, it was designed more to minimize bid price than to maximize total explosive energy. As a result, the total energy of the slurry obtained was less than that of TNT. It is possible to formulate a 10% aluminized slurry so that total energy would be 50% higher than the slurry which was evaluated. The resulting slurry would be more energetic than TNT and thus compare more favorably. If the TNT charges had been manufactured according to the design specifications, which modeled the DM 41A1 charges, a more meaningful comparison with the slurry explosive in terms of loading time and handling could have been made on the PC series.

AIR OVERPRESSURE MEASUREMENTS

For both the DRC series and PC series the dominant airblast mechanism was the gas vent pulse, which generally results when the rising mound of earth, on a cratering shot, disassociates, and vents the explosion gases to the atmosphere. For small-sized shots such as the ones described here, the primary damage mechanism from airblast is the static pressure in the blast pulse. Very little dynamic pressure can be expected since there is no large shock front. Damage predictions are thus based on predicted positive peak overpressures. The empirical prediction techniques discussed in Ref. 17 were used for this program.

The measured values are presented in Table 7 and plotted in Fig. 34. From Table 7 it can be seen that for the PC series the predictions were somewhat high and for the DRC series they were generally low. The lines of $R^{-1.2}$ dependence (range lines) indicated in Fig. 34 are drawn to produce a best fit to the data of all the PC and DRC shots. These lines represent an approximation of damage thresholds. The values for these reference lines are obtained from Ref. 18, which states that for conventional high explosives it may take 80-psi peak overpressure to cause fatalities, and a 5-psi peak to cause eardrum rupture. Studies at EERL[1] are in agreement with these values. By extrapolation of the fitted lines to the level of possible eardrum

rupture, it can be seen that rupture would not occur beyond 100 ft. Actual peak overpressures very close to ground zero will be lower than indicated by the extrapolated lines which tend to bend and fade when extended. Therefore, eardrum rupture would probably,not occur beyond 50 ft.

MISSILE STUDY

Figures 35-37 are quick references for determining troop safety distance in regards to missiles for the Armor Obstacle II series. If the information on minimum safe distances for personnel in the open presented in Ref. 19 was based primarily upon underground detonations and maximum missile range, the minimum safe distance for an 80-lb or 320-lb event would be 1/2 and less than 1/4 of these distances respectively.

In more recent studies at EERL,[14] the size and range of missiles ejected by cratering events that may be harmful to personnel have also been studied. It has been determined that any missile with a weight of 1/6 lb or greater may be dangerous to exposed personnel surrounding a cratering event.

Robert E. Shafer of Lawrence Livermore Laboratory, in a report on the probability of shrapnel hitting a given area,[20] indicates that the shrapnel from an aluminum bomb casing of 1/2-in. thickness packed with C-4 has a probability of 6×10^{-7} of hitting 1 ft^2 at 1000 ft from a detonation. If this is related to a 40-lb shaped charge and if the minimum safe probability of impact is 1×10^{-6}, then a range of 1000 ft from the ground zero of the detonation would be relatively safe for exposed personnel.

To make emplacement holes for the cratering charges for a portion of the DRC series, several shaped charges were used. According to Ref. 9 and 20, 1020 ft is the minimum safety distance for personnel in the open from 40-lb shaped charges. This value is similar to the predicted results (1000 ft) presented in Shafer's report. With the above information and the results of the A.O. II program, an evaluation of the most influential effects can be made.

Figure 34 indicates that at distances greater than 100 ft from the largest of the A.O. II cratering events, the airblast overpressure was small enough to cause no damage to the eardrums of exposed personnel near the detonation. The maximum missile range (the farthest distance from ground zero at which a missile was found) for all of the cratering events was 724 ft as shown in Table 9. Noting that the safety radius for missiles for exposed personnel greatly exceeds the safety radius for airblast overpressures, it is reasonable to assume that the missile safety radius determines the personnel safety radius for the A.O. II cratering detonations. However, it is also noted that the minimum safe distance as predicted in Refs. 9 and 20 for cratering with small row charges (DRC events) is 2000 ft and the minimum safe distance from the large row charges (PC events) is 3300 ft. Comparing these predicted values with the values listed in Table 8 and 10, it appears that for cratering in the Fort Peck media the minimum safe distances listed[9,20] can be reduced between 60 and 75% depending on the magnitude of the detonation.

SEISMIC INVESTIGATION

In all cases, predicted peak particle velocities were somewhat higher than those measured. A comparison of the measurements with the predictions indicates that the rate of attenuation of peak particle velocity with range is higher for the small yield DRC and PC experiments than for larger detonations previously conducted at the Fort Peck test area.[5,7] The largest seismic motion amplitudes, measured during the PC-1 detonation, indicate that the ground motion disturbances witnessed by troops located beyond the maximum missile range would not constitute a safety hazard to them or their facilities.

OBSTACLE EFFECTIVENESS STUDY

The DRC-1 crater was not very effective against the M-60 tank; as a result, neither of the tanks were evaluated in any of the other deliberate road craters. However, the DRC's proved to be more effective against the APC and the other tactical vehicles, as shown in Table 13. The main battle tanks were the only vehicles evaluated in the PC craters. The results indicate that neither tank had any difficulty negotiating PC-1. However, the tank driver's attempt to make a slight turn while trying to maneuver in the third hole of PC-2 prevented the tank from exiting the crater under its own power. The damage to the crater during the recovery operation prevented the subsequent evaluation of the M-48 in the PC-2 crater.

Out of the six 1-ton craters produced for Project Diamond Ore IIB with nitromethane, only two presented formidable problems for the two tanks.

The 7-ft deep opening in the lip of the 6-M crater proved to be ineffective. The field expedient detonation failed to reduce the slope of the crater sufficiently for the tank to reach the opening (as shown in Fig. 45).

Chapter 5. Conclusions

Data recovery for the three series of experiments was outstanding. Analysis by Sandia and the WES Laboratories indicates 99% recovery of data for the PC and DRC detonations. Except that the slurry was not as energetic as called for in the test design (and hence produced smaller craters than were anticipated) the results of the experiment were encouraging.

Although the contractor met the specifications for the desired explosive (Table 10), it appears that rather than issuing a stock item, a new batch was formulated which met all of the specifications but with lower energy than that assumed by the test designers. In terms of total energy, the mix received was on the lower end of the spectrum, which indicates that the minimum total energy specified may have been too low. Discussions with the slurry explosive manufacturer following the experiments at Fort Peck revealed that in terms of relative effectiveness the slurry issued was rated to be 30% less effective than

the TNT used in the PC series (PC-1), this comparison being based on a series of underwater energy tests. This would account for difference in the crater dimensions and excavated volumes between PC-1 and PC-2 because in effect 30% less explosive was used for the PC-2 detonation (see Table 1). If a 10% aluminized slurry with a manufacturer's effectiveness rating of 1.3 over TNT had been used, the resulting crater dimensions might have been closer to the predicted values. A reevaluation of the cratering effectiveness values for slurry explosives of varying explosive properties (specifically total energy) relative to conventional explosives is required in order to adequately write specifications for a desired slurry product.

The results of PC-1 and PC-3 (Table 4) suggest that the cratering effectiveness value for nitromethane in terms of excavated volume of material is very close to that of TNT as indicated in Ref. 1. However, until a boostering system has been tested and proves able to overcome the problems experienced with the PC-3A hole, and a technique is devised to expedite the loading of a 500-lb drum, the use of nitromethane for PC craters does not appear to be very practical. There also appears to be very little difference in crater dimensions between concrete lined holes in PC-1 as opposed to the unlined chambers in PC-3.

Use of the 18-in. corrugated pipe in the PC hole to facilitate loading and unloading the slurry explosive did not appear to contribute to any crater dimension. The difference in heights of the explosive column of PC-2A and PC-2C (Fig. 8) apparently had no effect on the craters in terms of their dimensions or excavated volume (Table 1). Empty 55-gallon drums may still be used as explosive containers in existing prechambered holes if the exterior walls of the drums are smooth (i.e., without support rings). These containers could conceivably be preemplaced during or after chamber construction. If a change in mission is possible that requires removing the bags of slurry that were dropped into the PC chambers, recovery ropes should be attached to the slurry bags and tied off at the top of the chambers.

The DRC series of tests showed by the results of DRC-1 and DRC-4 the apparent feasibility of employing slurry explosive in fewer emplacement holes in a medium similar to clay shale to produce a road crater which is as effective as one which can be produced from the Army's present DRC design. This phenomenon was more recently verified during the Raystown deliberate road crater experimental program conducted in the more competent clay shale deposits found near Huntington, Pennsylvania. A full report on the Raystown project is currently being prepared. A comparison of the results of DRC-2 and -3 suggests that slurry explosives have a tremendous advantage over conventional explosives in their ability to fill all voids in an emplacement hole and thereby take advantage of the resulting excellent coupling with the media. The size of the crater which resulted from pouring the slurry into the five emplacement holes of the standard design suggests that larger crater dimensions may have been achieved if the slurry had been poured into the emplacement holes of the new designs that were tested.

The dimensions of deliberate road craters predicted in Fig. 5-25 of Ref. 9 and Fig. 5-34 of Ref. 20 are larger than were observed in this test. References in field manuals to predicted crater dimensions are not presented with any exceptions due to differences in media. The results of this study indicate that the Army's present manuals may be misleading and should be altered to reflect that the estimated crater dimensions can be expected when working in <u>most</u> media. Additional tests would have to be conducted in several different materials to predict accurately, according to a three or four part media classification system, the crater dimensions the reader could expect.

The effectiveness of the new design (DRC-4) indicates that it may be very effective to employ two or three ammonium nitrate canisters per hole to achieve the same results as the DRC-1 design.

It appears that reducing the number of emplacement holes for a DRC from five to three and using slurry explosives could conceivably reduce a squad's preparation time by 30 to 45 min (or about 40%). A greater savings on emplacement time will probably depend on the differences in media and the adequacy and number of excavation tools a squad is equipped with to meet the design requirements for the emplacement hole.

The AN-ANFO series confirmed that ANFO is comparable to a mixture of ammonium nitrate and TNT in cratering effectiveness (i.e., to a 40-lb crater charge).

The airblast data obtained indicates the overpressures were generally within a factor of 2 of those predicted. Existing troop safety distance tables on missile throw-out and airblast over-pressures for the range of slurry explosive charges fired would require no changes.

Results of the PC detonations in terms of crater dimensions vividly point out the feasibility of employing slurry explosives as an alternative to TNT for making obstacles in a medium similar to Bearpaw clay shale. Staggering the PC emplacement holes may be more effective than placing them in a straight line. If the craters produced are slightly staggered, as they were for PC-3, and the tank driver is forced to change his direction in a loose material such as clay shale, the probability of losing a track is very high. The inability of tracked tactical vehicles to change direction easily in a soft loose material without losing a track was also observed during the mobility study of Project A.O. I.[2] Future row cratering tests should be designed to ensure that movement through the resulting craters will be impossible without changing direction.

A crater is considered to be an effective obstacle if a trapped vehicle has to make more than two attempts to get out of it.[9,10] Under this definition, all of the PC, DRC, and D.O. craters can be classified as obstacles to wheeled and most tracked vehicles as a result of the go/no-go evaluation conducted. The time required to move through any of the craters was reduced by 75 to 80% once the obstacle had been breached by the first vehicle. Although these craters were classified as obstacles, their effectiveness in terms of the amount of time an enemy would have been delayed would depend largely upon the cover each one

was afforded and the manner in which they were employed. Without proper observation, the lips of a single PC obstacle could probably be reduced by a bulldozer, making the obstacle passable in less than 10 min, which is more than the average time a single tank took to move through the three holes. A 30-meter bridging capability would not have been adequate to negate the effectiveness of the gap created by the prechambered holes.

If the XM-180 cratering kit could be modified to perform consistently in all media and produce the same results as in sandy clay, it would definitely be an improvement over the Army's present cratering designs. Future WES slurry explosive cratering programs should also include the firing of several XM-180's due to the time and manpower savings associated with the employment of these cratering kits.

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Appendix A
Crater Profiles and Cross Sections

This appendix depicts the crater configurations of Project Armor Obstacle II. Included are topographic and isopach maps and drawings of crater profiles.

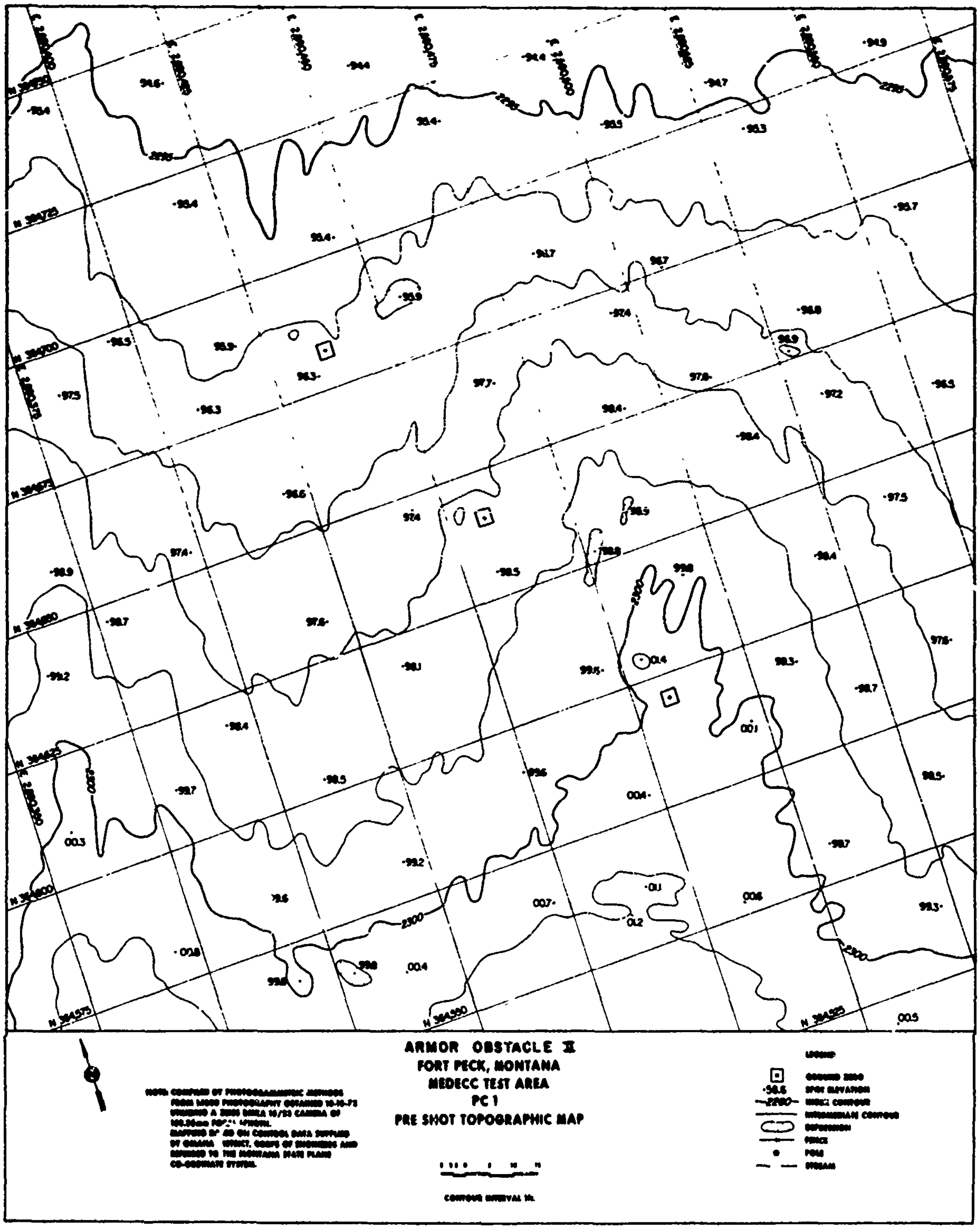

Fig. A1. PC-1 preshot topographic map.

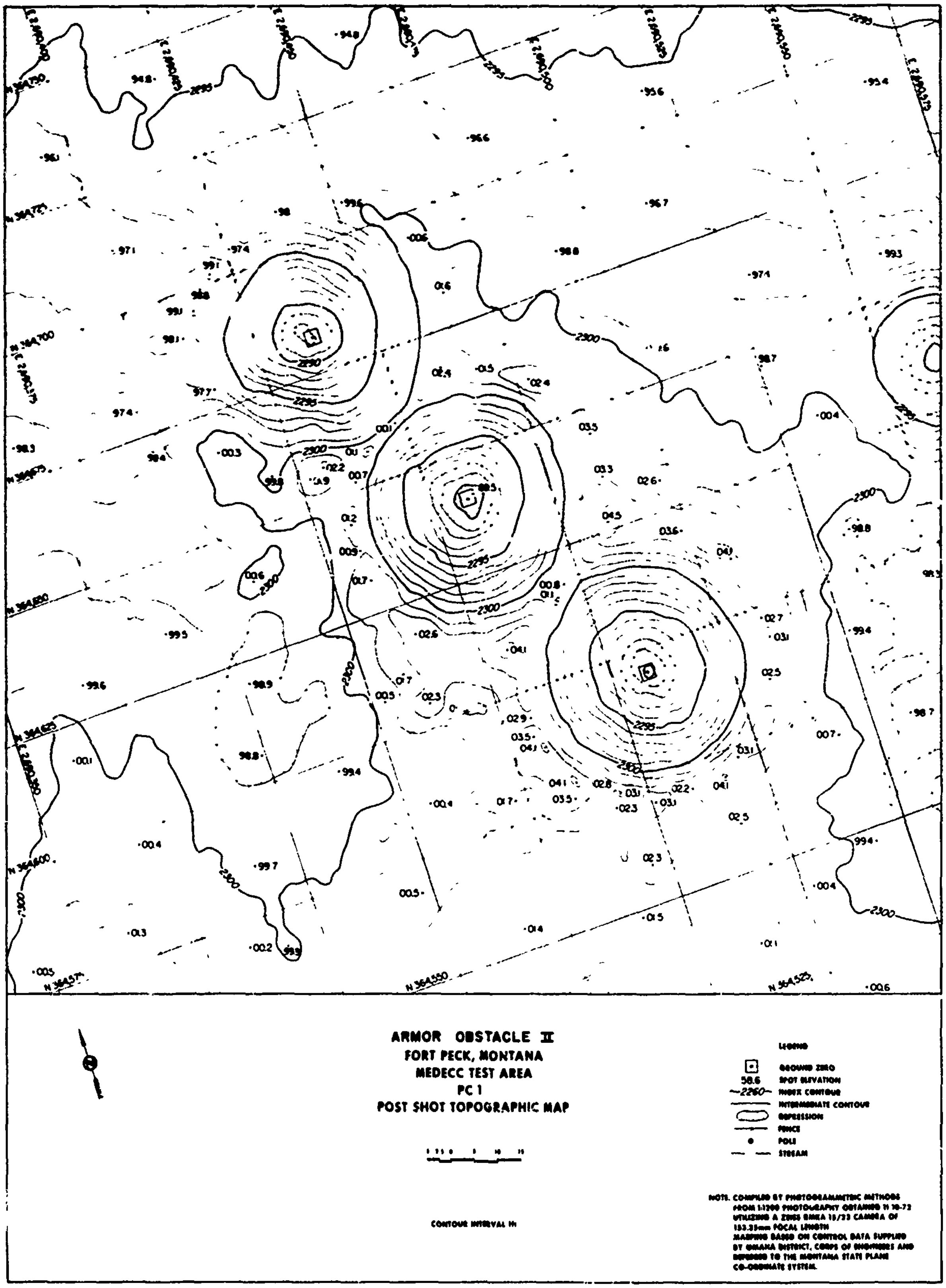

Fig. A2. PC-1 postshot topographic map.

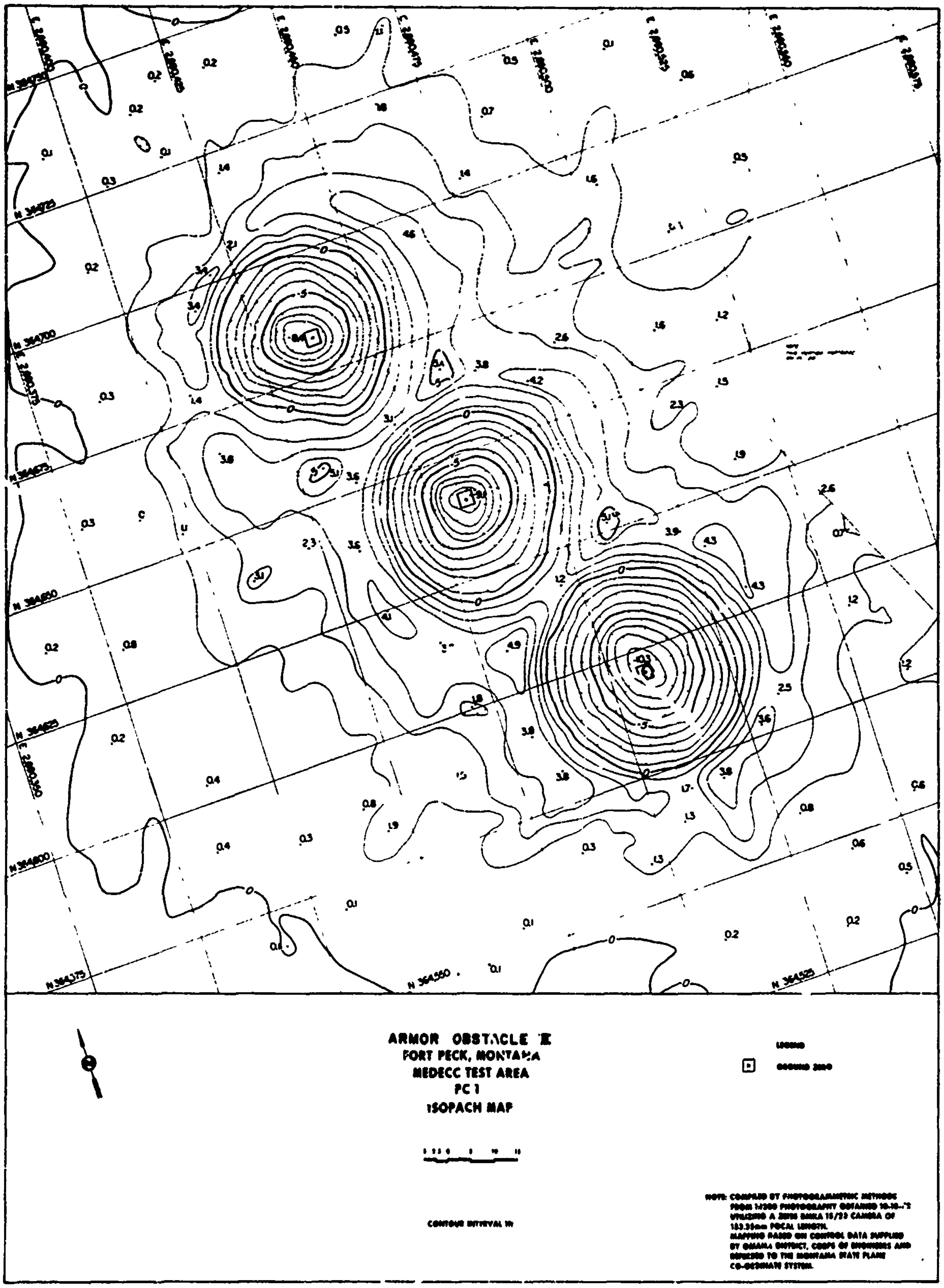

Fig. A3. PC-1 isopach map.

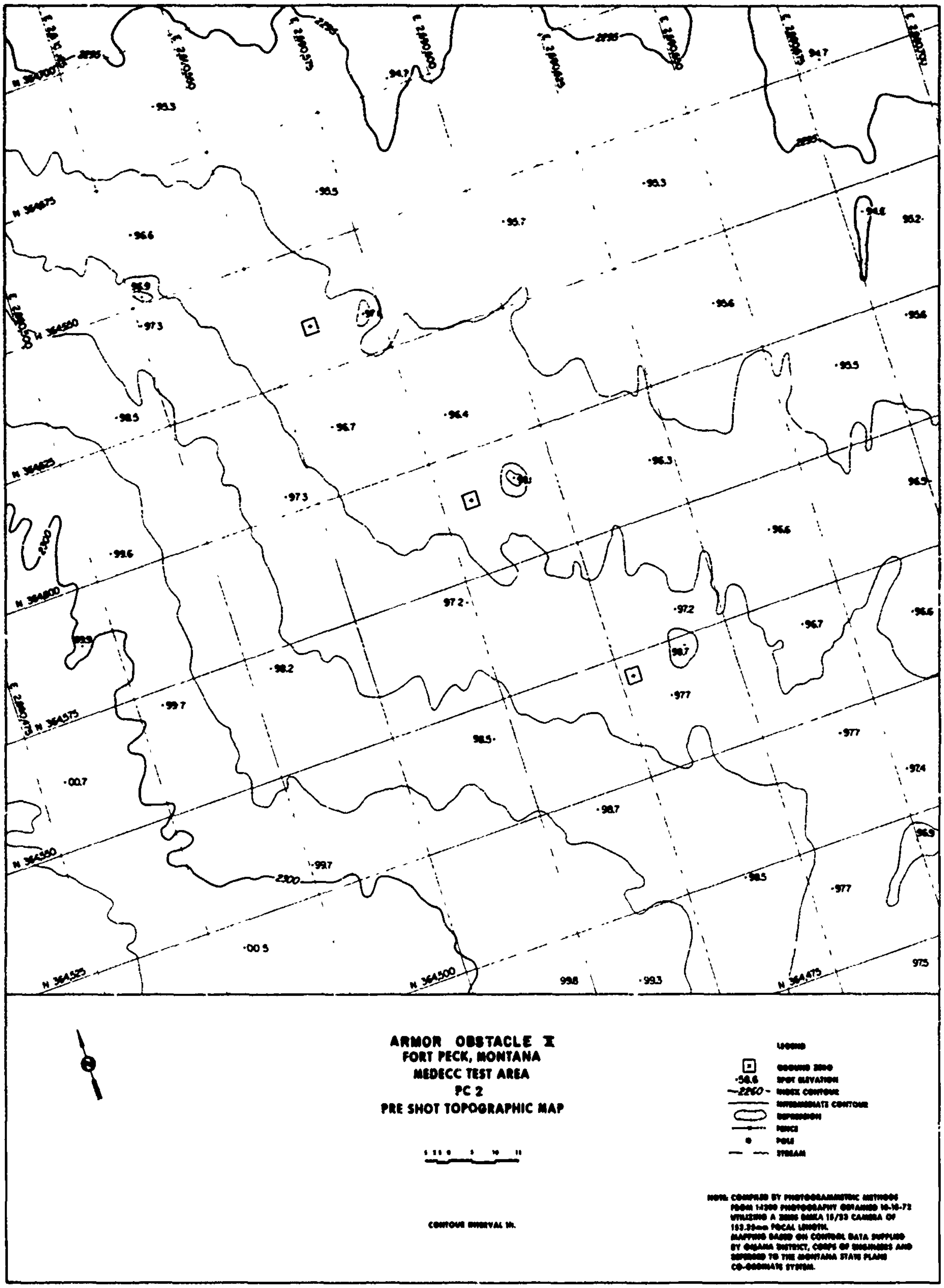

Fig. A4. PC-2 preshot topographic map.

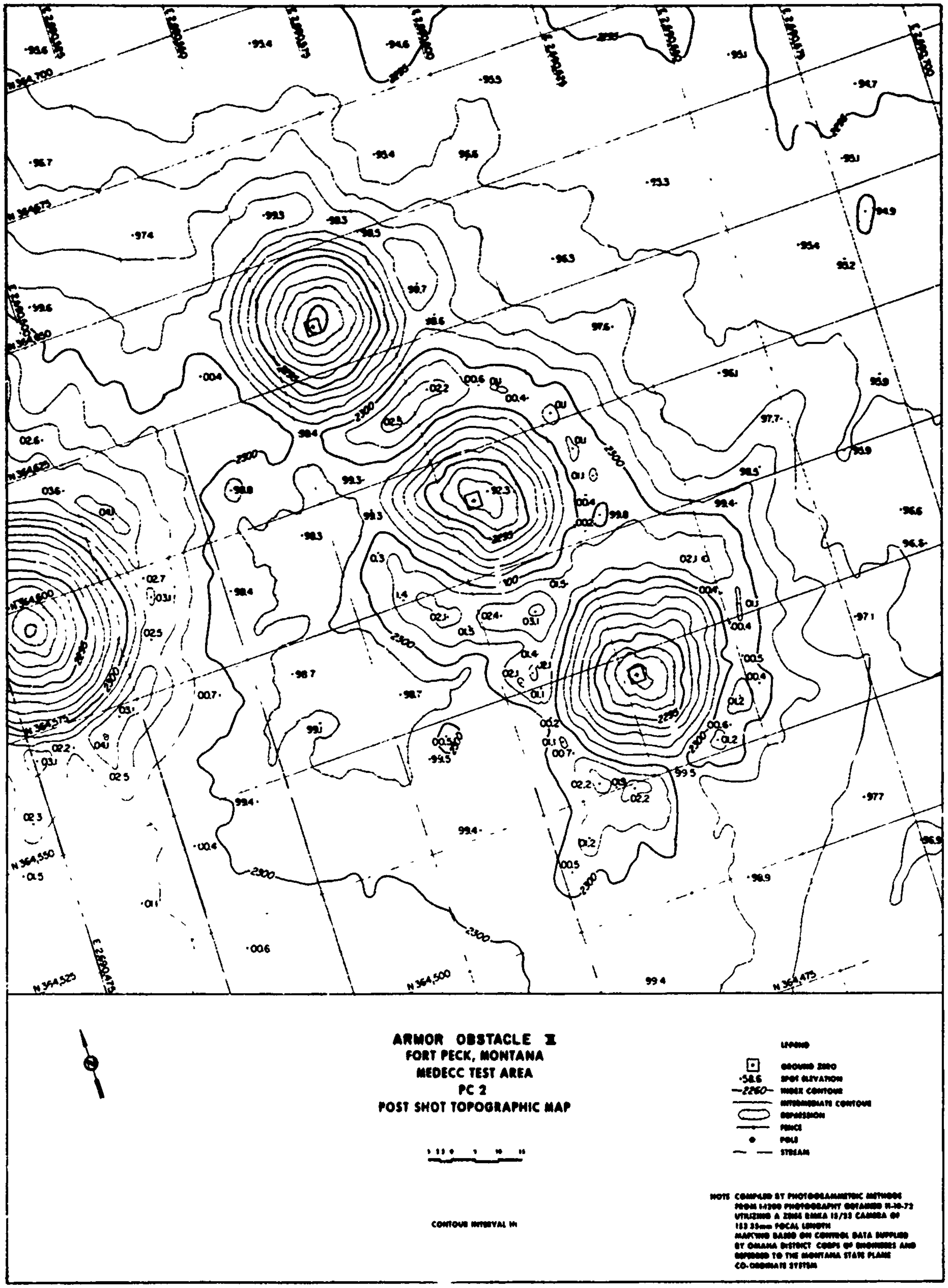

Fig. A5. PC-2 postshot topographic map.

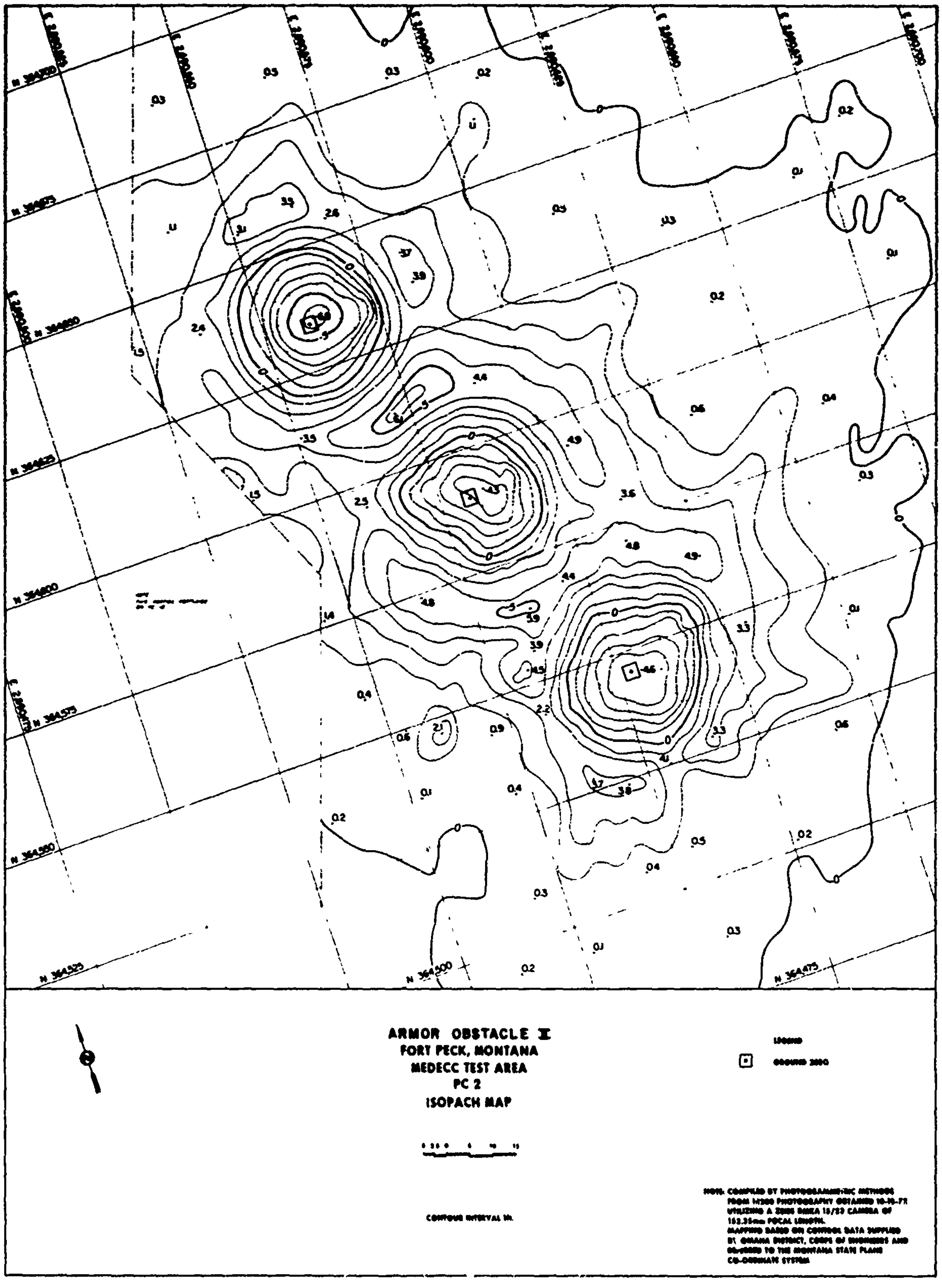

Fig. A6. PC-2 isopach map.

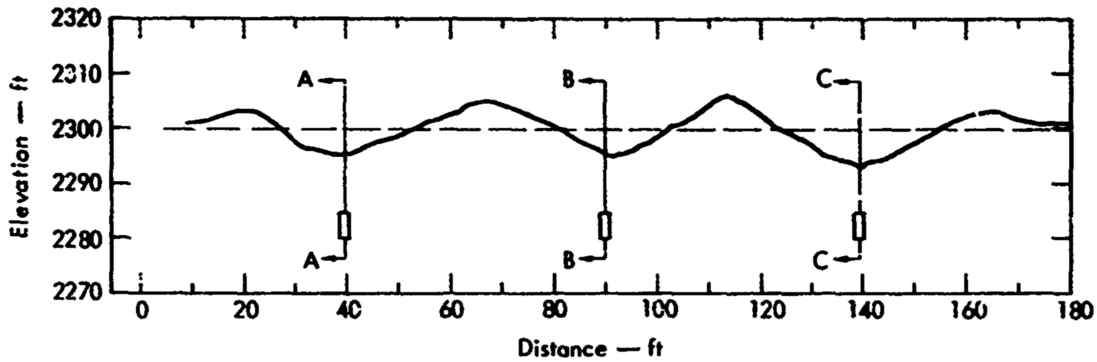

Fig. A7. PC-2 longitudinal profile.

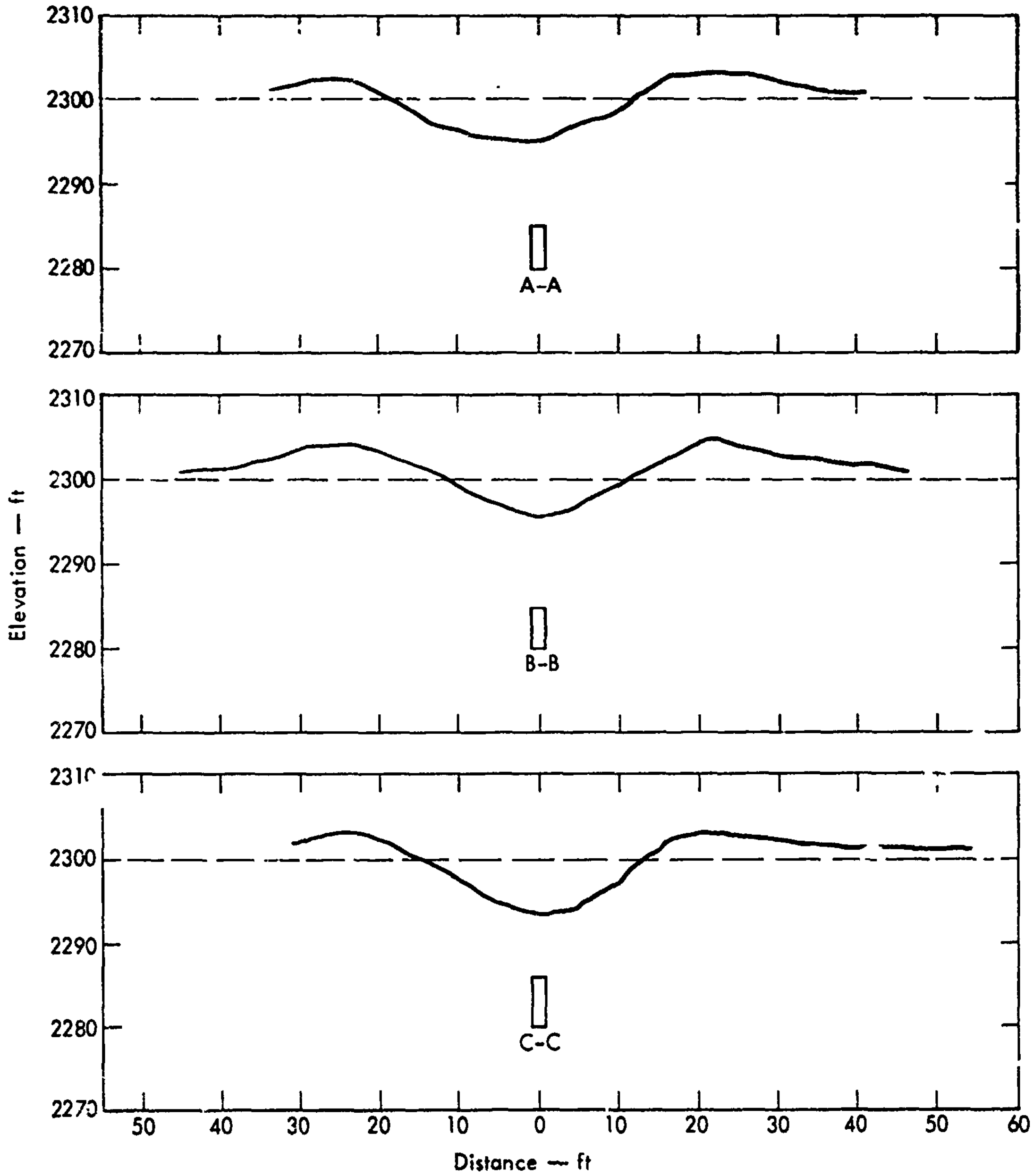

Fig. A8. PC-2 cross-sectional profile.

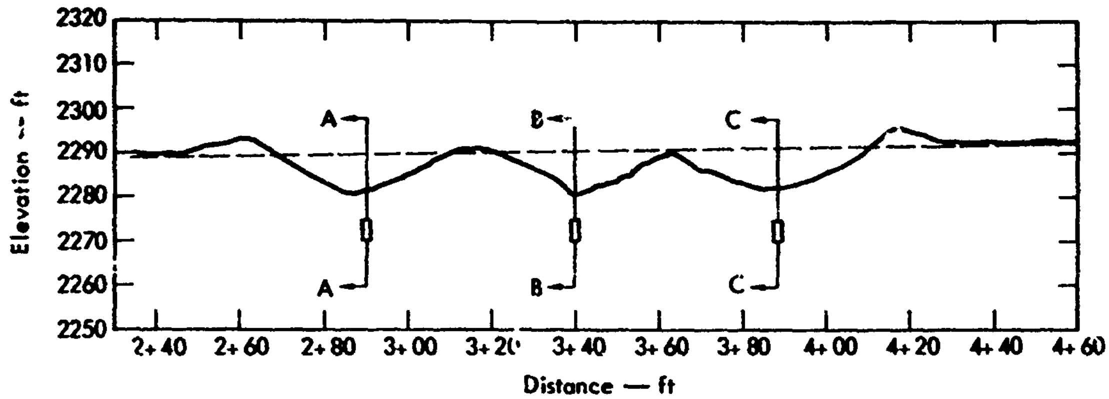

Fig. A9. PC-3 longitudinal profile.

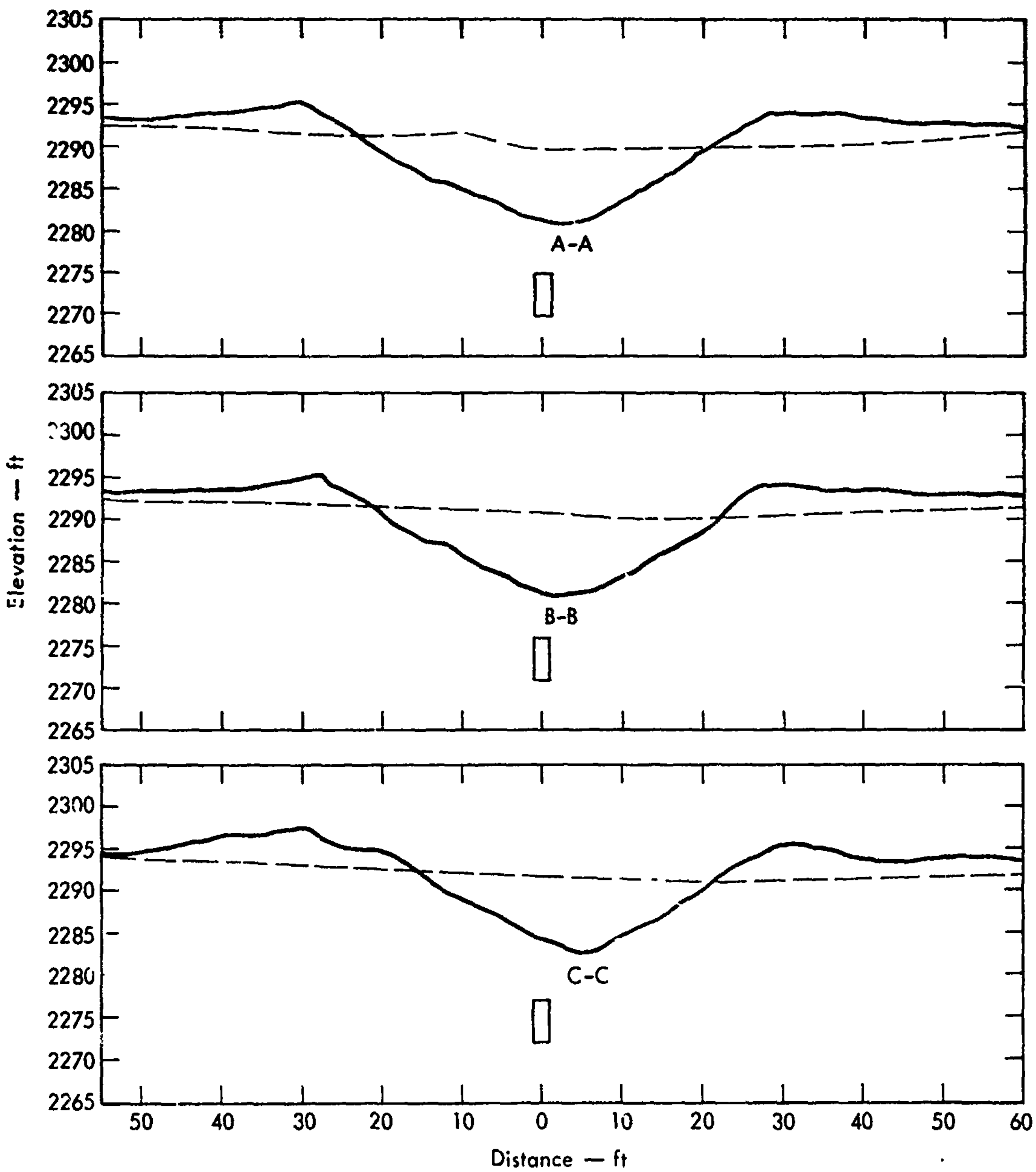

Fig. A10. PC-3 cross-sectional profile.

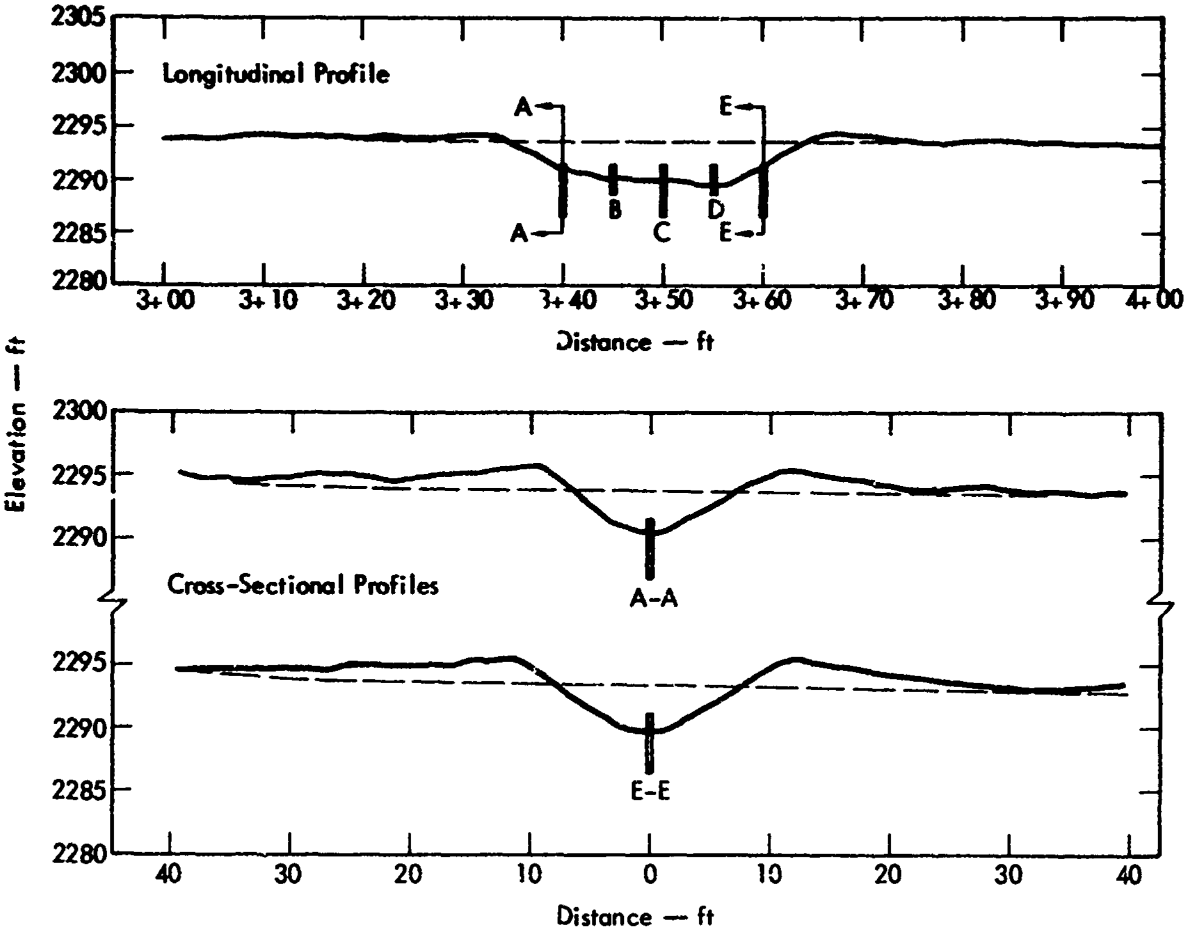

Fig. A11. DRC-2 longitudinal and cross-sectional profiles.

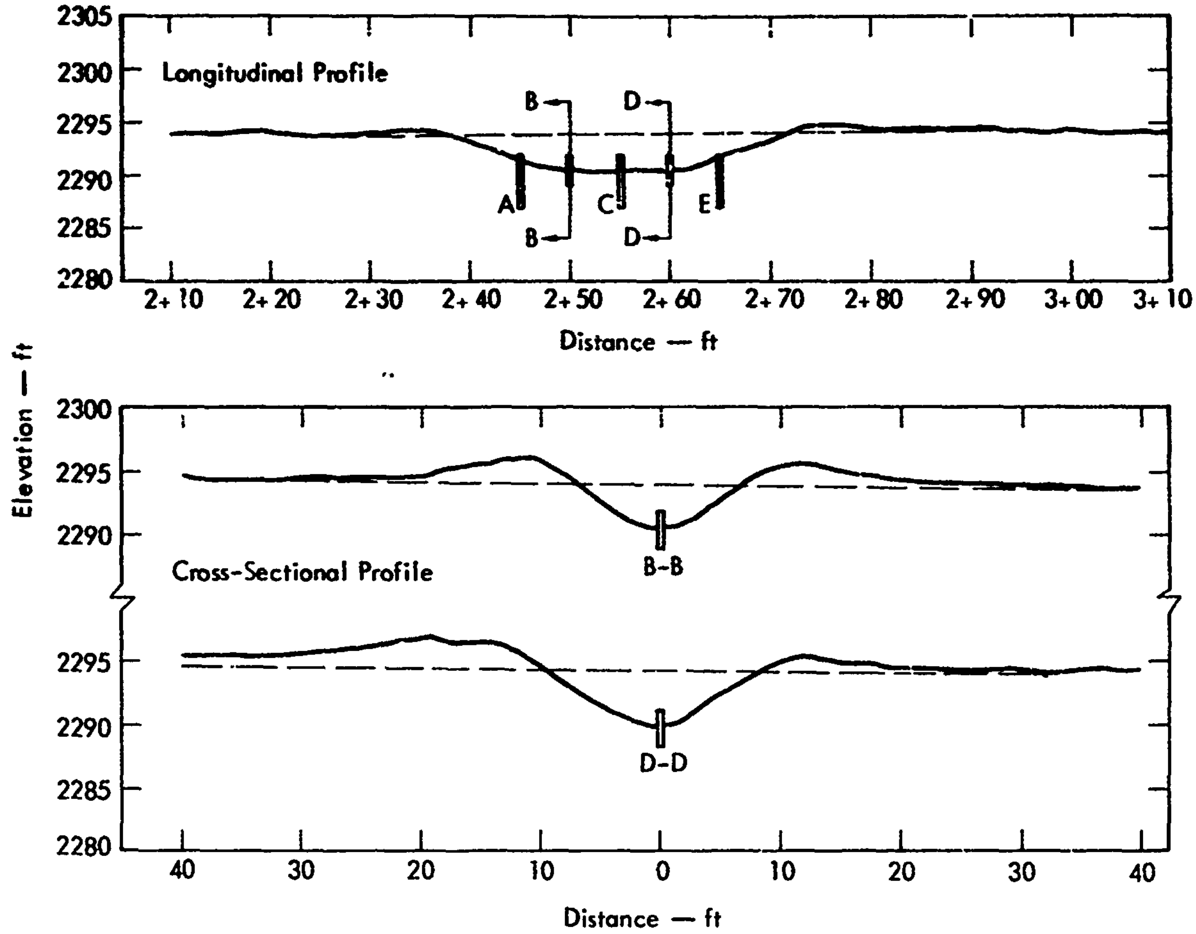

Fig. A12. DRC-3 longitudinal and cross-sectional profiles.

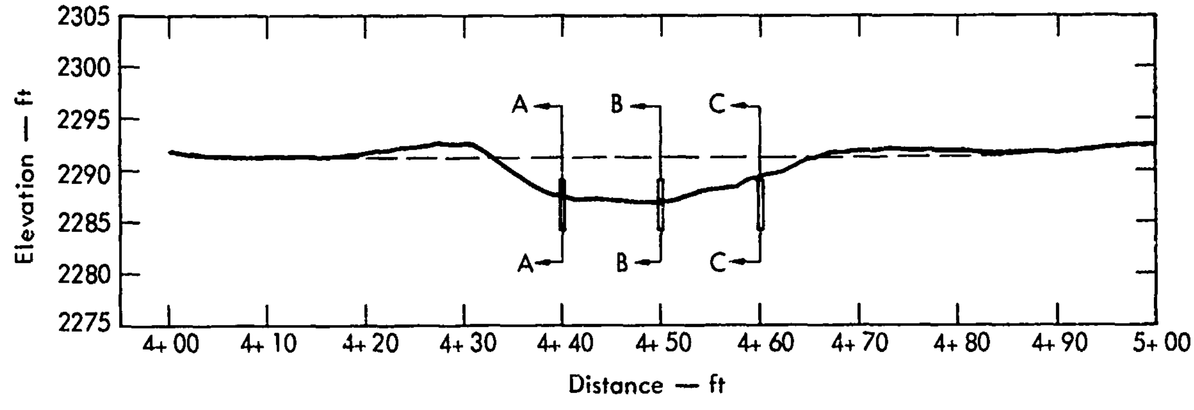

Fig. A13. DRC-4 longitudinal profile.

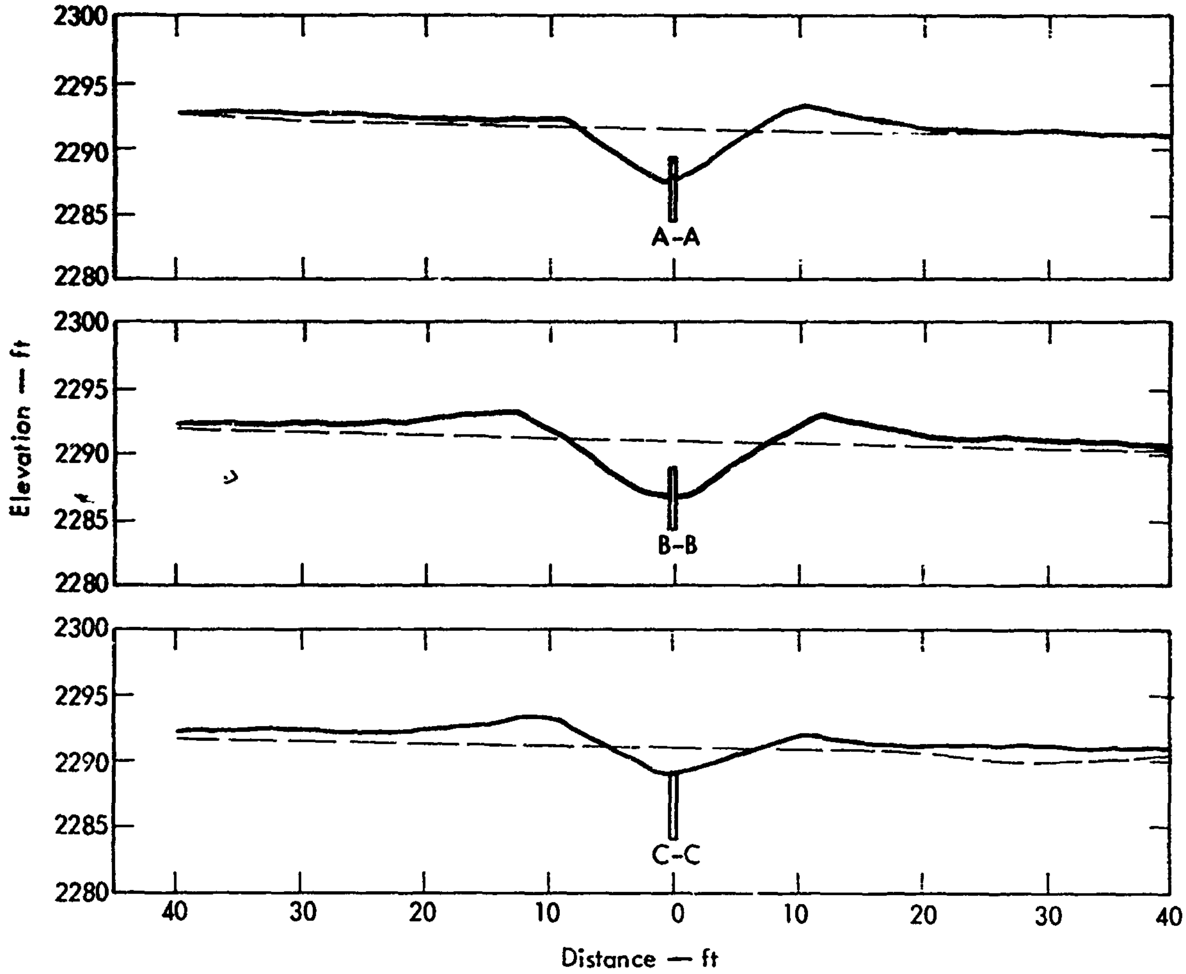

Fig. A14. DRC-4 cross-sectional profile.

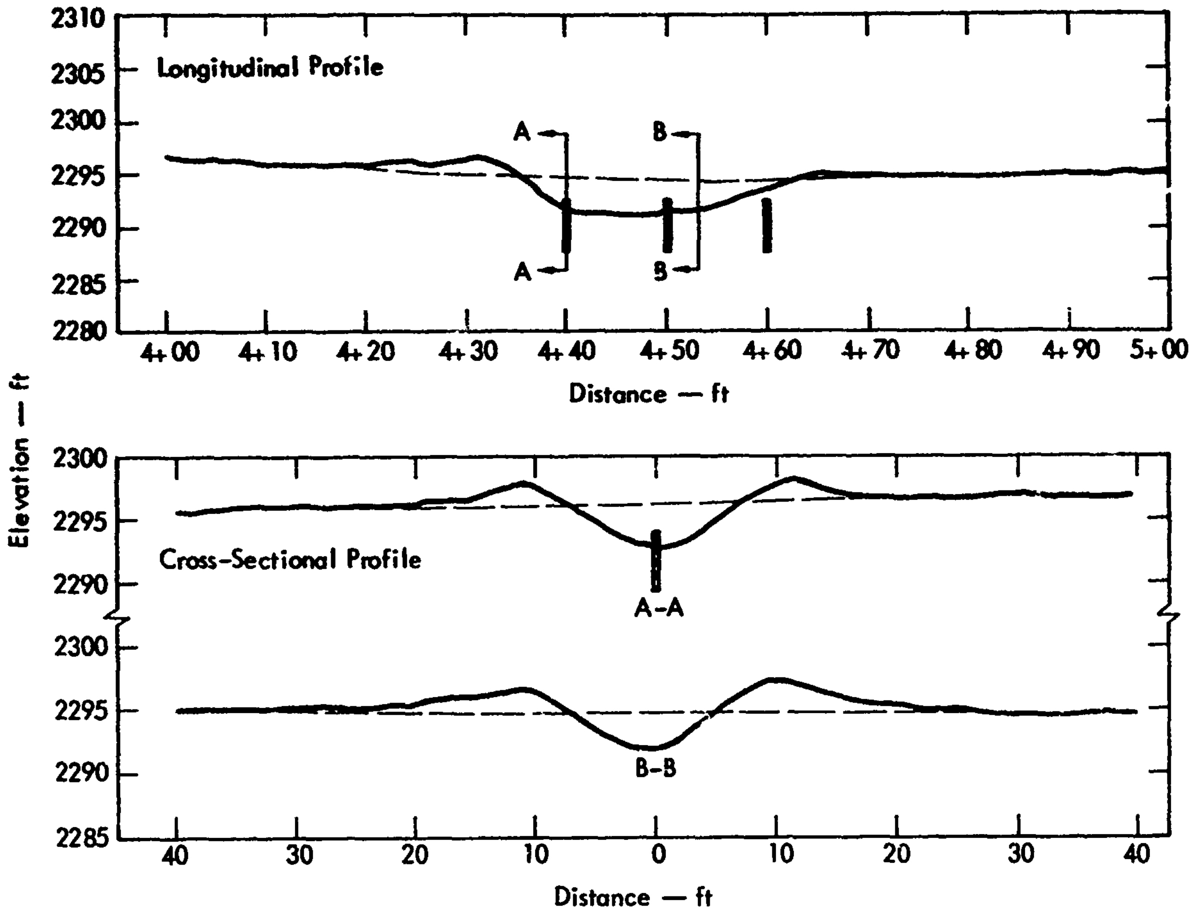

Fig. A15. DRC-5 longitudinal and cross-sectional profiles.

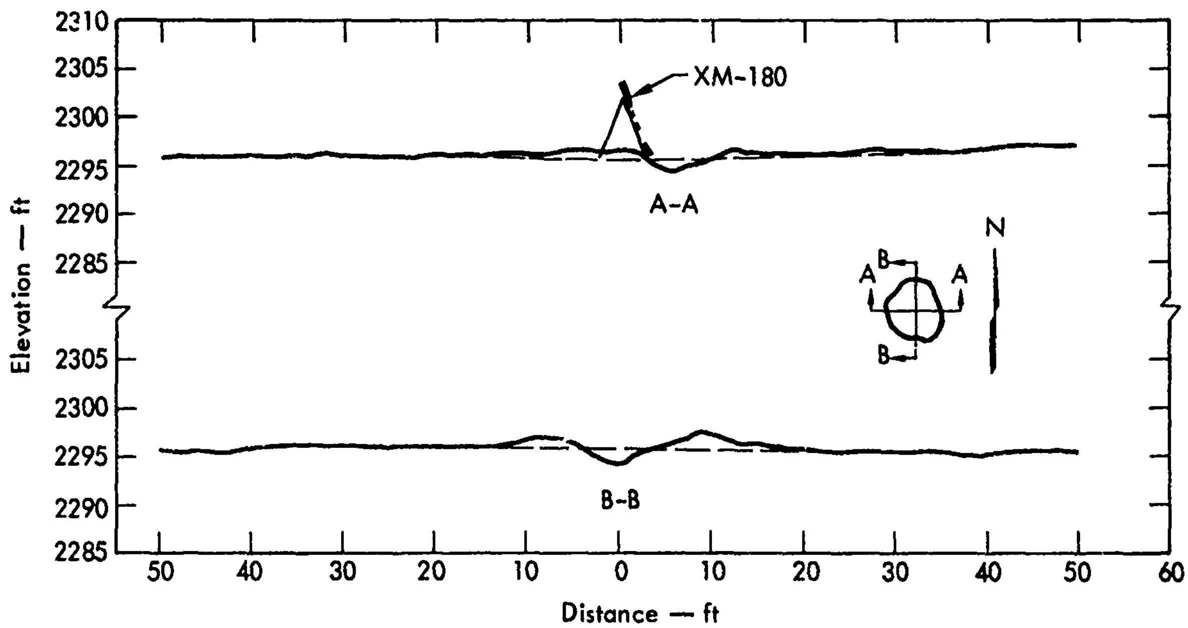

Fig. A16. XM-180 cross-sectional profile.

Appendix B
Ground Motion Data

This appendix contains the ground motion data collected during Project Armor Obstacle II.

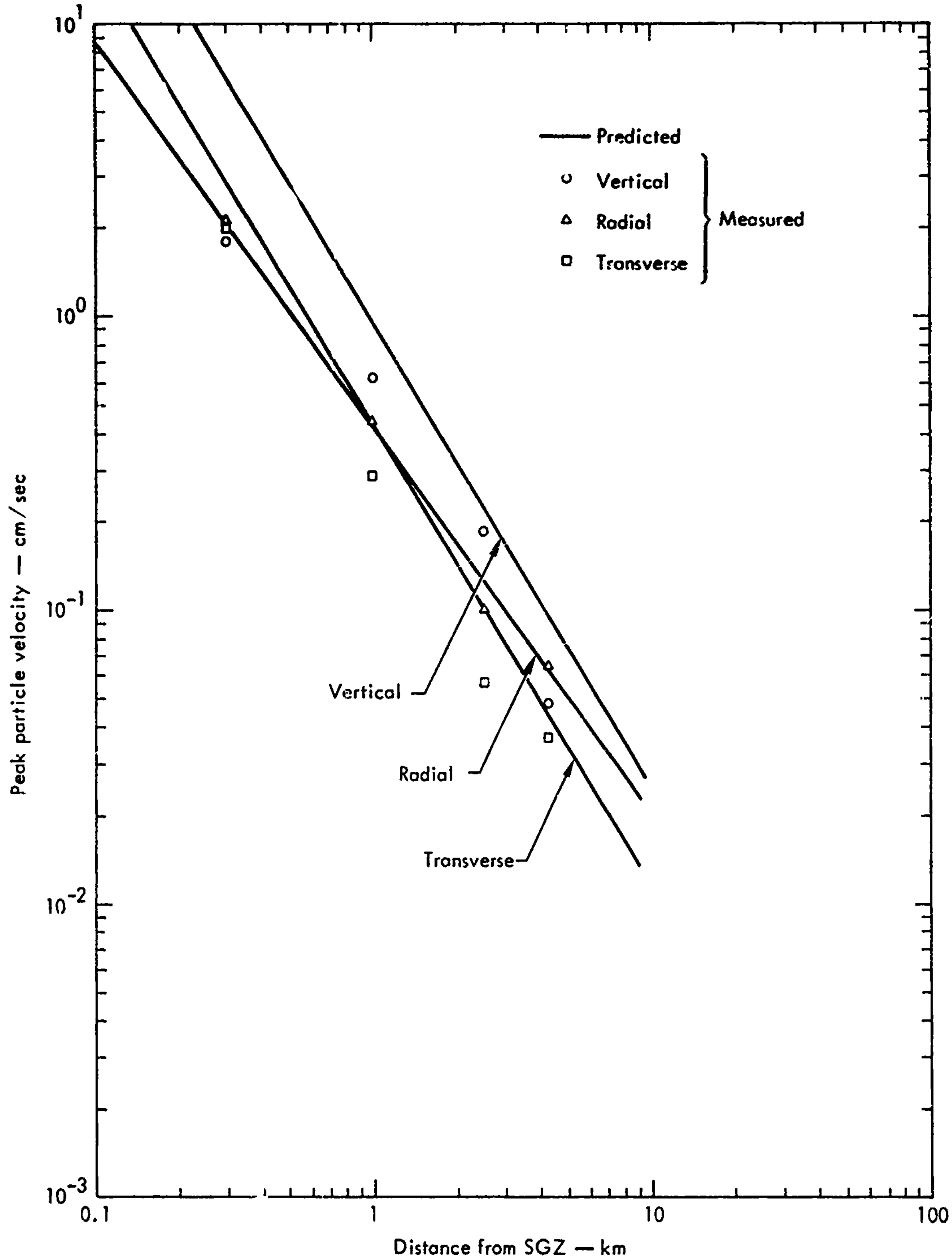

Fig. B1. Predicted and measured peak surface particle velocity as a function of distance for PC-1.

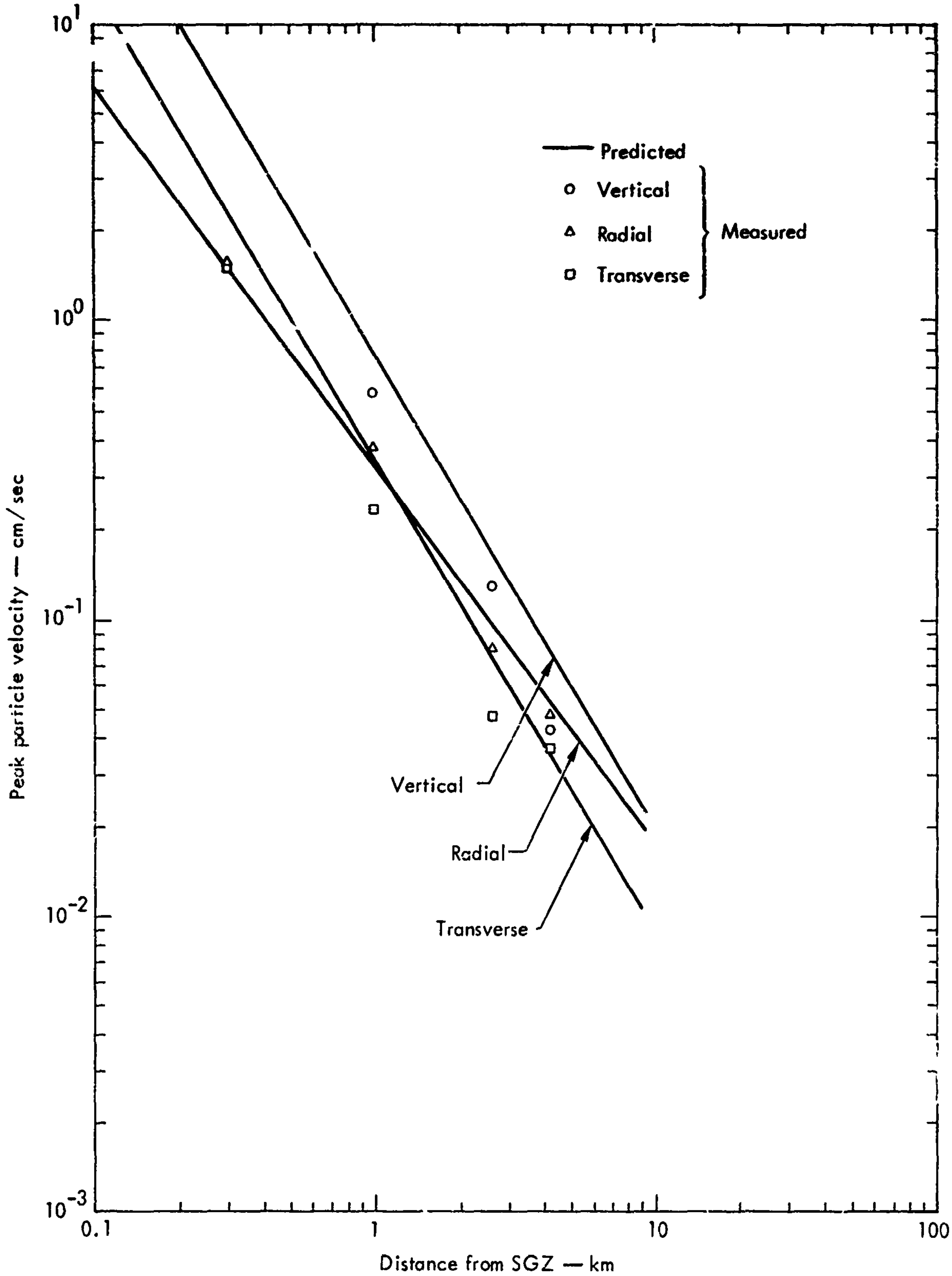

Fig. B2. Predicted and measured peak surface particle velocity as a function of distance for PC-2.

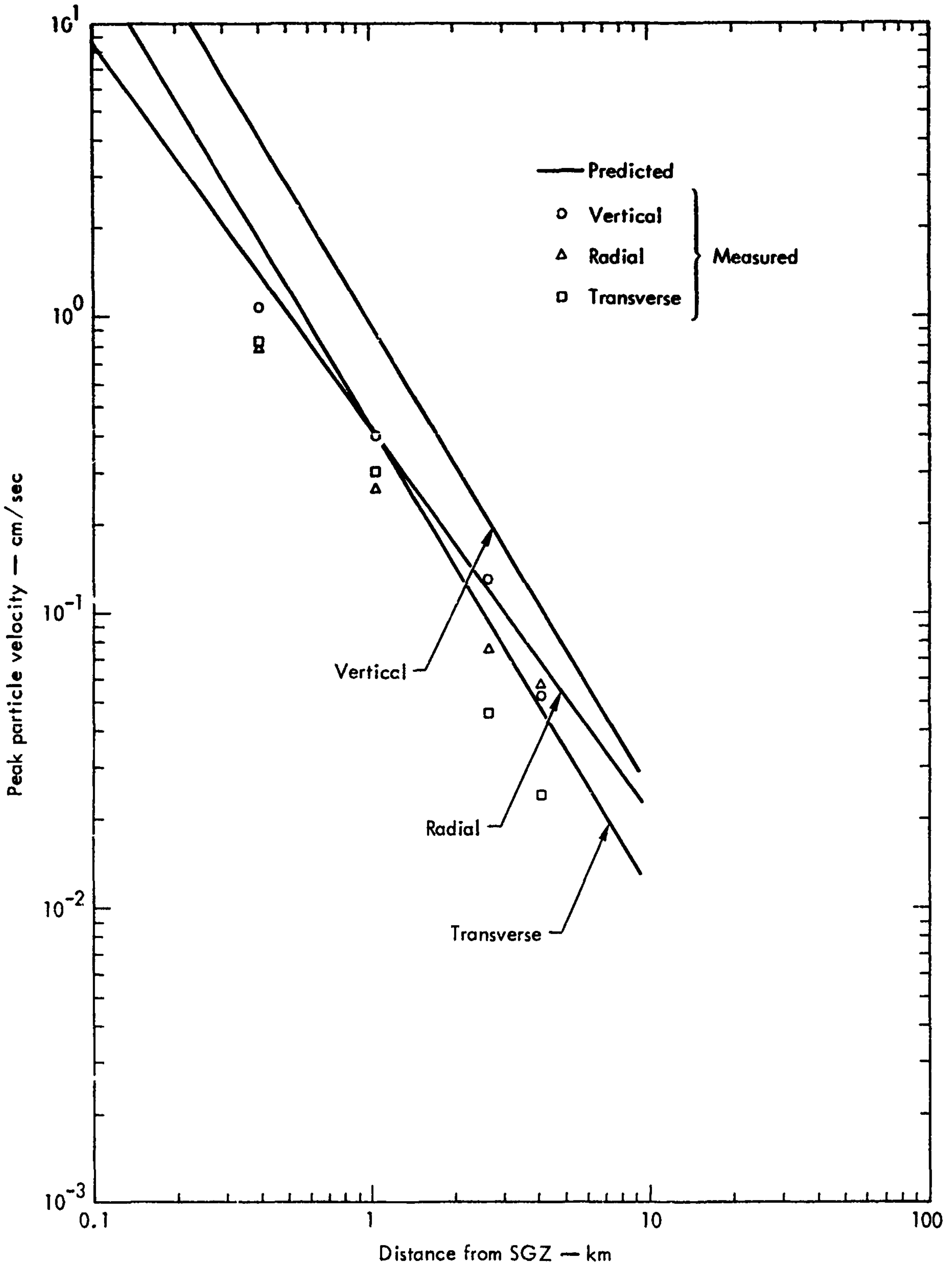

Fig. B3. Predicted and measured peak surface particle velocity as a function of distance for PC-3.

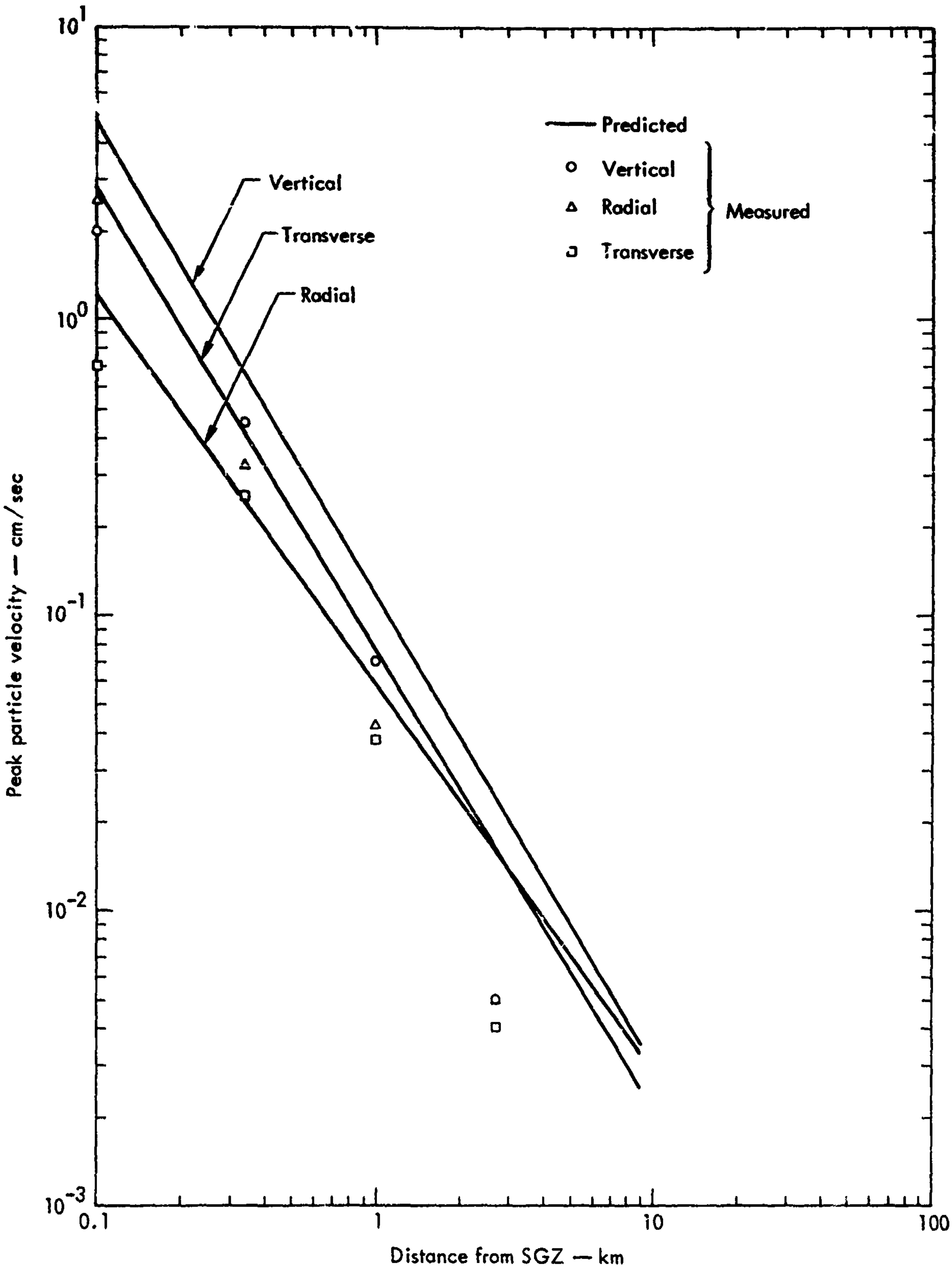

Fig. B4. Predicted and measured peak surface particle velocity as a function of distance for DRC-1.

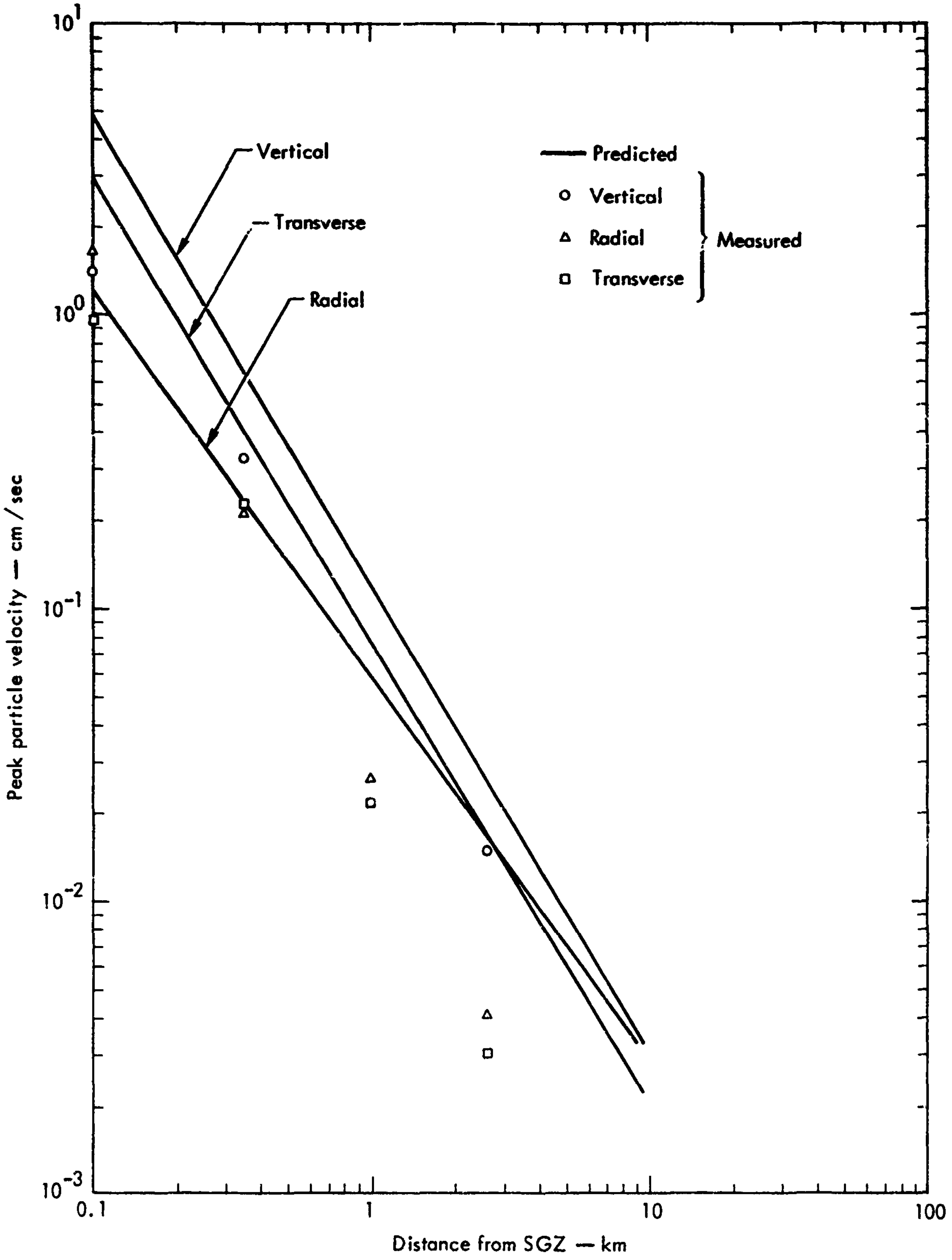

Fig. B5. Predicted and measured peak surface particle velocity as a function of distance for DRC-2.

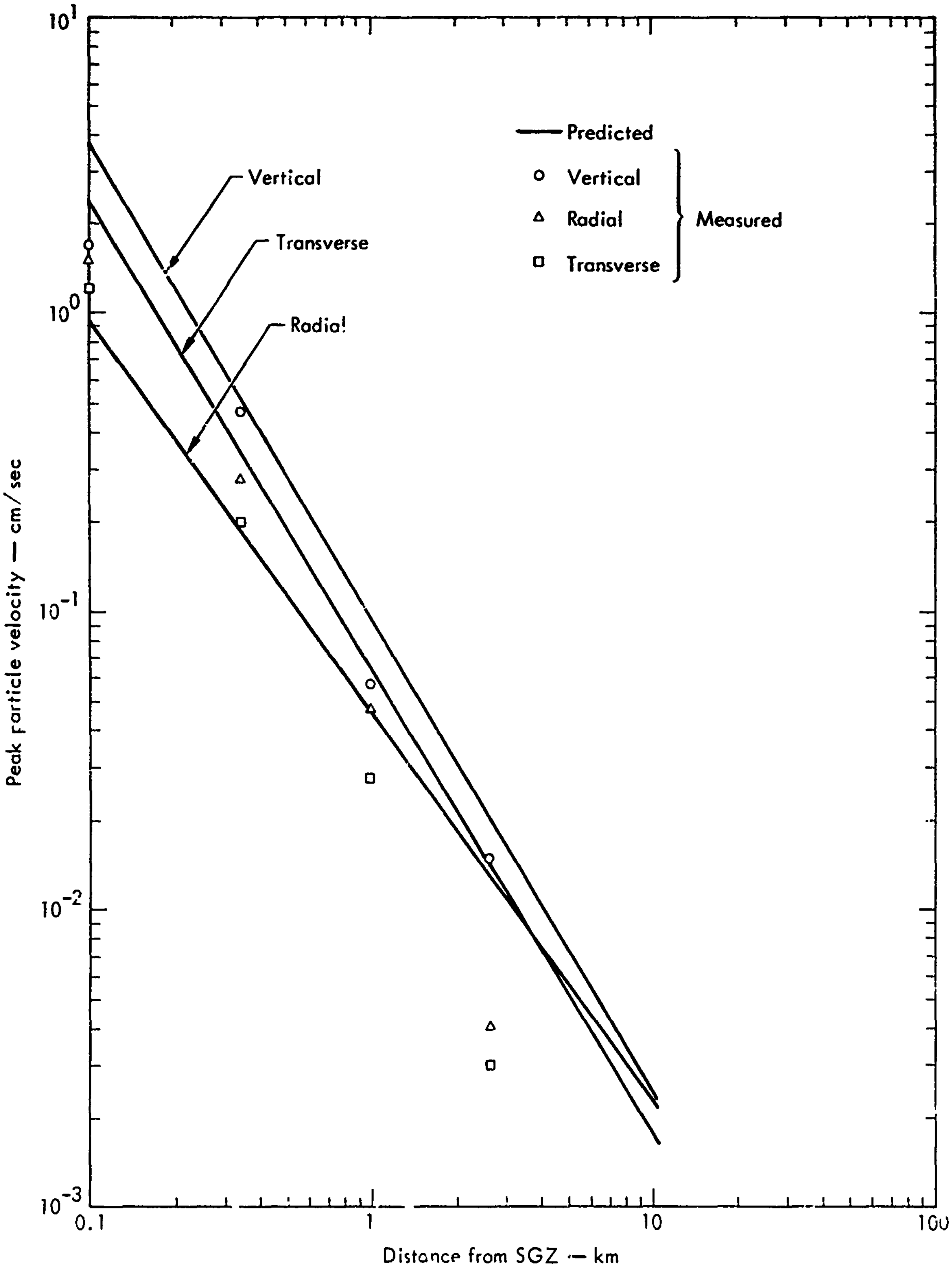

Fig. B6. Predicted and measured peak surface particle velocity as a function of distance for DRC-3.

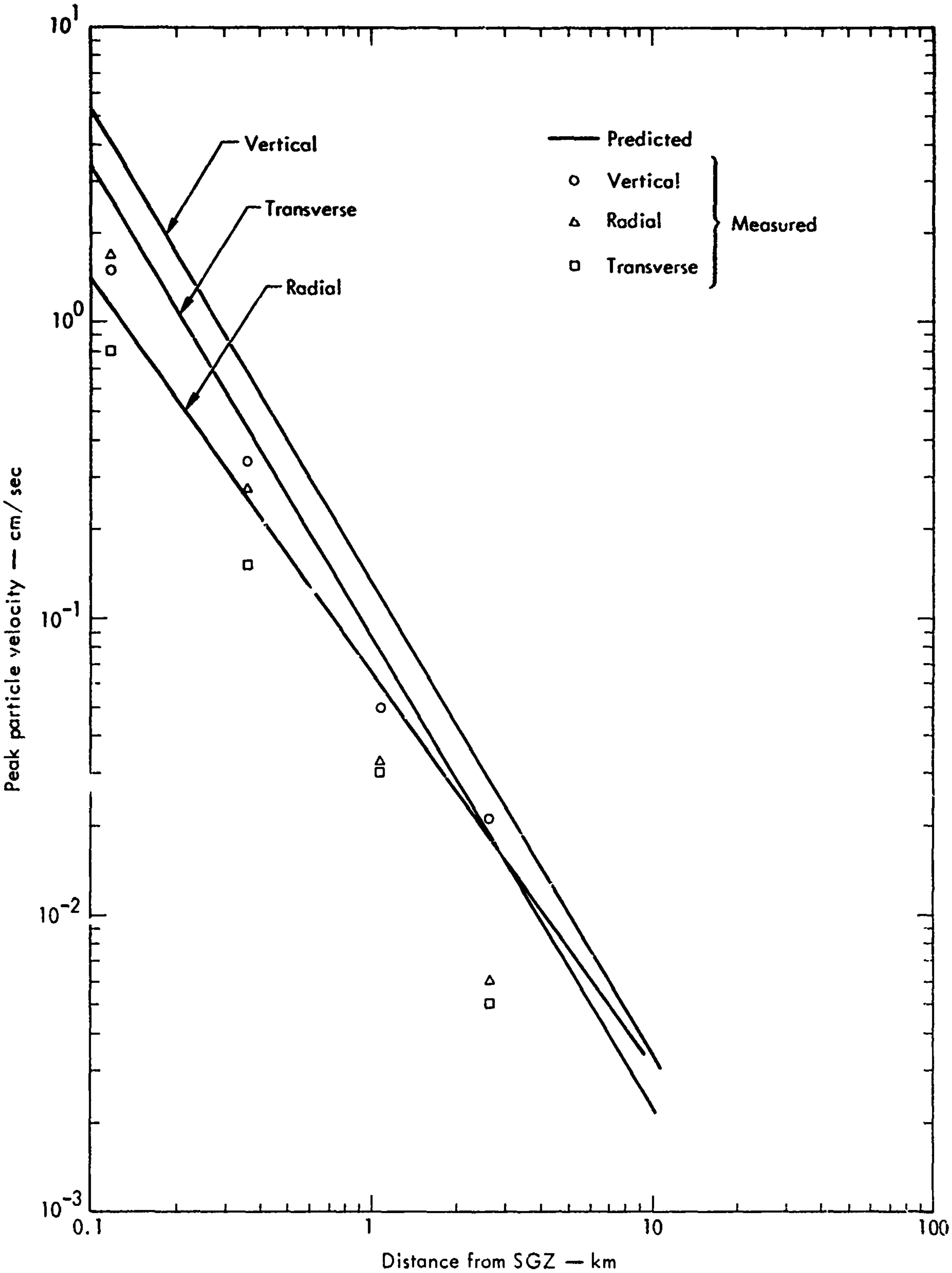

Fig. B7. Predicted and measured peak surface particle velocity as a function of distance for DRC-4.

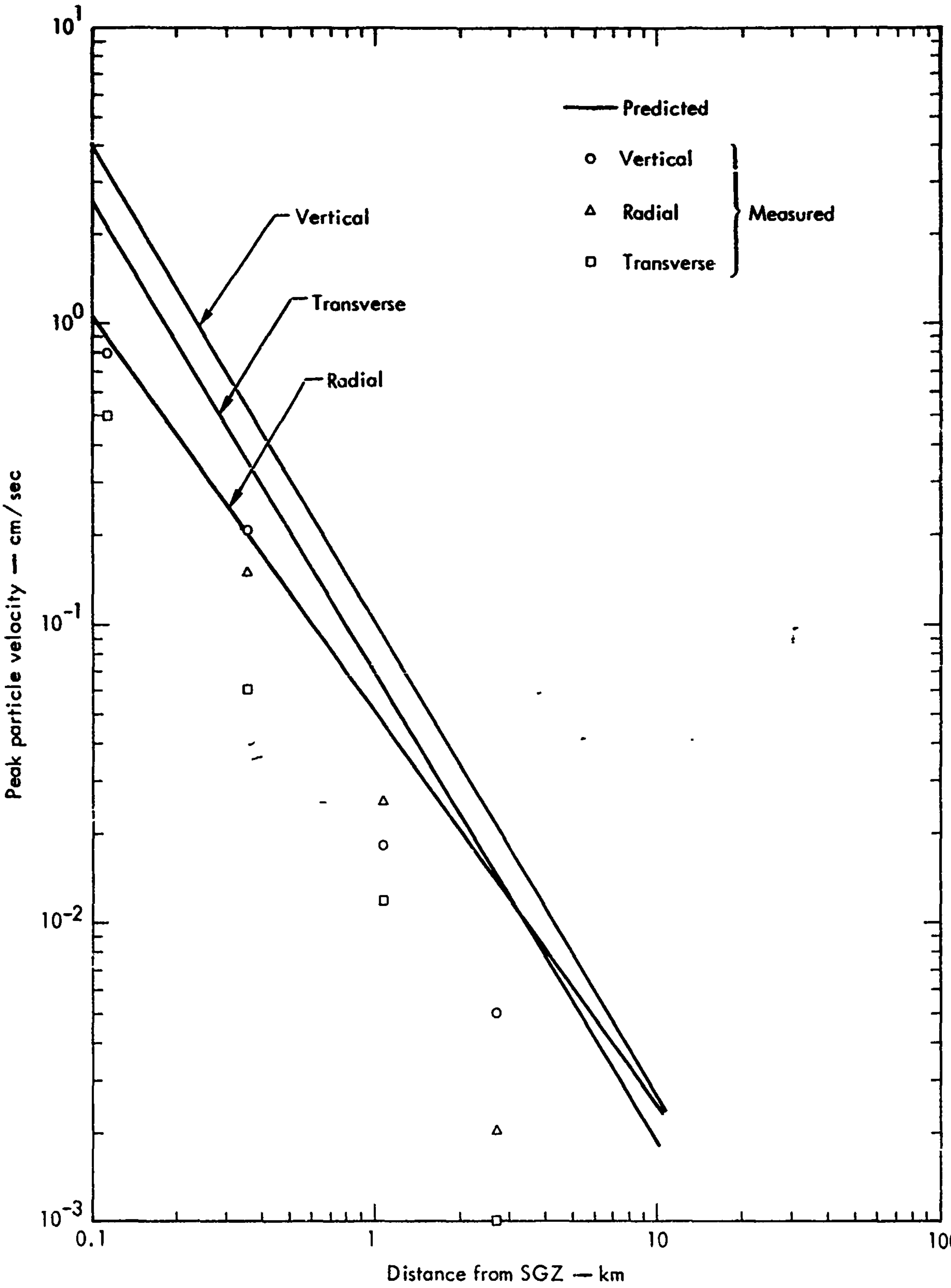

Fig. B8. Predicted and measured peak surface particle velocity as a function of distance for DRC-5.

Appendix C
Mobility Test Equipment and Observations

Figures C-1 through C-6 of this appendix show the vehicles that were used in the obstacle effectiveness study, and a summary of their physical characteristics is given in Table C-1. An edited transcript of the observations recorded during the mobility tests is also included in this appendix. It is the work of MAJ Roy Hovey of the U.S. Army Armor School. The dimensions given are his rough approximations; detailed crater measurements are given in Table 5 of this report.

MONTHLY TEST OBSERVATIONS (Edited Transcript)

IT-3 Crater

The M-60 entered the IT-3 Crater on the morning of 7 November 1972. The crater was about 25-30 ft in diameter and 15-18 ft deep. The charge weight on this shot was 1 ton.

The M-60 A-1 appeared to be having mechanical problems and was not operating under full power in the forward gears. In my opinion either the M-60 A-1 or the M-48 A-1 could have scaled this crater after several runs to pack down the soil. The M-60 A-1 did not appear to be immobilized when it reached the bottom of the crater.

However, if any of the material had been set, or tended to become slippery, the 1-ton craters would have been extremely effective in immobilizing the tanks. The shape of the 1-ton crater, being almost a perfect cone, tended to offer considerable resistance to the nose and underbelly of the tank. Subsequent tests were conducted for this crater on 12 November after repairs were made on the M-60 A-1. After several attempts the tank was able to exit this crater under its own power.

6-Meter Crater

Tests in the 6-Meter Crater took place on 8 and 9 November 1972. The crater was reported to be about 180 ft in diameter and 50 ft deep. The charge weight used was 17 tons.

It was agreed by all concerned with the operation that the M-48 A-1 probably would not make it out of the 6-meter crater without assistance before the operation began. However, the engineers were

Fig. C1. M-60 Main Battle Tank.

Fig. C2. M-48 Battle Tank

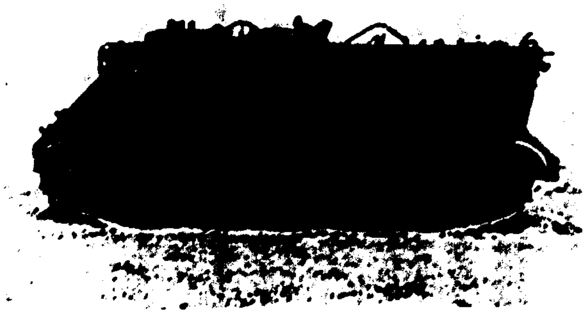

Fig. C3. M-113 Armored Personnel Carrier.

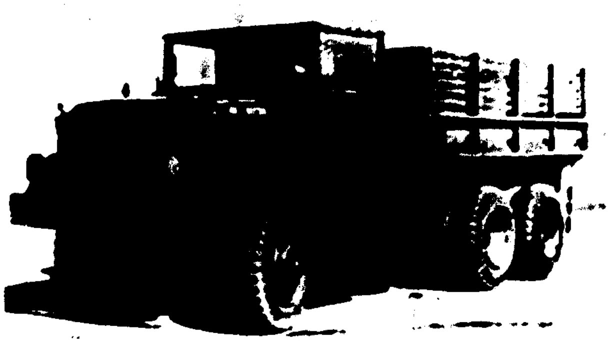

Fig. C4. M35A1 Truck, Cargo, 2-1/2 ton.

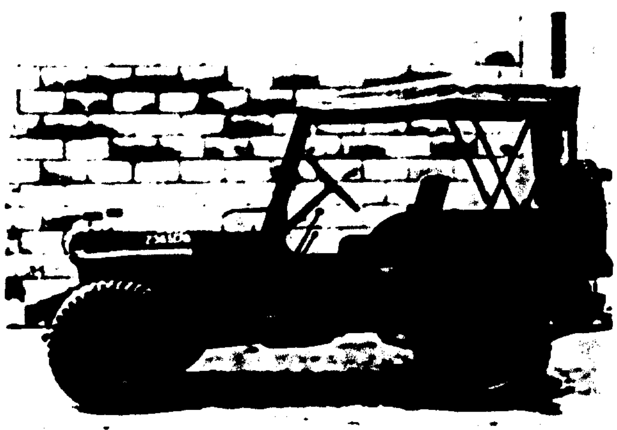

Fig. C5. M38A1 Jeep.

especially concerned with the type of assistance needed and the time involved in providing it. The driver entered the crater at a moderate speed, was slowed

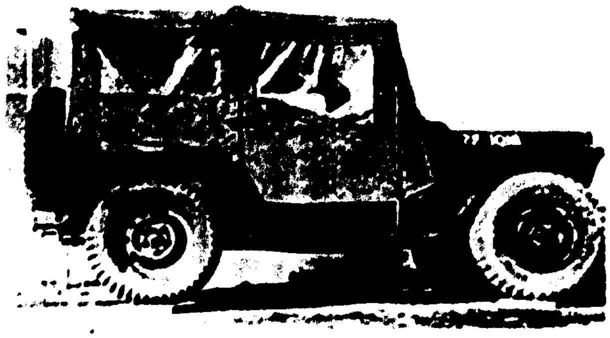

Fig. C6. M151A1 Jeep.

considerably by the loose material on the bottom of the crater, and did not move appreciably above the floor of the crater until the tank had packed down the loose material. As I remember, the tank made it slightly more than half way up the original ground surface before throwing a track. One of the cardinal sins a tank driver scaling a crater can commit is to try to execute a violent turn while in the bottom of the crater. After the track had been repaired on the morning of 9 November, an International Harvester bulldozer began reducing the slope of the crater. Times and specific details were recorded on tape. The bulldozer reduced the slope and compacted the earth considerably so the M-48 made it through the crater on the first try. The M-60 A-1 followed, but had mechanical problems. It left the crater on the entry ramp under its own power.

IT-5 Crater

The IT-5 Crater was tested on the afternoon of 9 November. The crater was about 30 ft in diameter and about 15 ft deep. Charge weight used was 1 ton.

The M-48 A-1 tank driver entered the crater slowly and stopped at the bottom.

Table C-1. Characteristics of tactical vehicles employed in Project Armor Obstacle II.

Vehicle	Combat loaded gross wt (lb)	Overall dimensions (in.) Length	Width	Height	Wheel base (in.)	Contact area of each track (in.)
M-60 Battle Tank	105,000	274	143	126	—	171 × 28
M-48 Battle Tank	104,000	271	143	123	—	162 × 28
M-113 Armored Personnel Carrier	23,380	192	107	98	—	105 × 15
M-35 Al Truck	18,900	278	96	115	154[a]	—
M-38 Al Jeep	3,490	139	61	73	81	—
M-151 Al Jeep	3,200	133	64	68	85	—

[a] Front axle to midpoint between tandem rear axles.

He moved back and forth across the bottom several times, going as much as 3/4 of the way back up to the original ground surface on the side he had entered on. The driver appeared to be losing a considerable amount of climbing power by shifting to low gear after he hit the bottom of the crater, as he came to almost a complete stop. This leads me to believe that the running speed across the crater is not the most important aspect. In several instances the tank moved just as far up the slope of the crater from a standing start from the bottom of the crater as it did with a running start. In most instances observed, the best technique was a slow even forward turning movement of the tracks with no violent changes in direction once the tank had started to ascend the side of the crater. Spiraling attempts must be ruled out as the tank will walk right off the tracks when it begins to cant. The tanks that threw tracks did not reach 30% tilt in the spiraling efforts.

The M-48 tank attempted to breach the IT-5 crater on the afternoon of 9 November. The driver of the M-48 A-1 seemed to have very little trouble negotiating this crater. He used the technique of entering the crater straight on, with the tank level and moving at a slow speed. As I remember, he stopped at the bottom as soon as the soft earth started offering resistance to the tank. After several straight backward and forward movements to compact the loose clay shale he started moving up the side of the crater. Two or three runs were necessary to pack the shale down enough so the tank could break through the lip of the crater and climb out. On all of the tests it was noted by the observers that the tanks could often make it up to the level of the original ground, but the soft earth of the crater lip tended to interfere with the traction of the tank once this point was reached. The driving technique on this one was the best observed. The slow, deliberate movements appeared to offer the least mechanical abuse to the tank of all the techniques observed.

DRC-1 Crater

The trafficability tests through DRC-1 took place on the afternoon of 9 November.

The crater was about 35 ft long, 15 ft wide and 6-7 ft deep. The charge weight used was 320 lb.

The M-48 A-1 did not experience any great difficulty with DRC-1. It appears that the crater was not quite deep enough to offer resistance to the nose of the tank. As the crater was shallow, the width and length did not appear to add to the obstacle. The tank needed only one or two passes to compact the shale and then moved through the crater. It is my opinion that had this crater been 2 or 3 ft deeper it would have been a serious obstacle to the tank, as the width of the crater was not excessive. Again, soil conditions would determine the effectiveness of this crater. If the soil had been wet, the tank would have nosed down and would have been unable to climb out on the far side of the crater.

XM-180 Crater

The XM-180 was fired on 9 November. It created a crater about 17-18 ft in diameter and 2-3 ft deep. A large rock may have deflected the blast causing the device to perform much more poorly than expected.

It is my opinion that, from an Armor standpoint, the XM-180 offers great potential. It would definitely offer greater flexibility to the organization employing the device than do the methods requiring the drilling of cavities for emplacement of the explosive. As it requires little preparation and can be fired immediately after setting up, there is a minimal chance that the required craters cannot be emplaced at the proper time as a result of enemy action. Due to the simplicity of the device it may be expedient to have it emplaced by Armor and Infantry units in contact with the enemy, relieving the Engineers to prepare more sophisticated barriers. The XM-180 may prove to be an ideal device to reduce the lip of craters and reduce the slope. Use of these devices to move the lip back into the crater may be more effective than the conventional method of emplacing explosives tried on 10 November 1972.

Explosive Breaching of 6-Meter Crater Lip

A combination of explosives totaling 240 lb was used to create a gap in the lip of the 6-meter crater on 10 November. The gap was about 14 ft wide and 8-13 ft deep.

The material removed from the rim of the 6-meter crater was adequate to allow the passage of an M-48 A-1 or an M-60 A-1 once it reached the original ground surface. It was my impression that even with several runs the tanks would probably not reach that point unassisted due to the nature of the sides of the crater. Perhaps a repetition of the same charge in the original ground might move enough shale into the crater that the tank could make it out after several runs. It appears that both the steep slopes and the tremendous volume of soft shale that the tank must overcome make this crater an especially difficult obstacle.

PC-2 Crater

The PC-2 crater was tested on the afternoon of 11 November. The crater was about 45-50 ft in diameter and 10 ft deep. A total of 3000 lb of slurry were used to make the crater.

The M-60 A-1 entered the first of the three separate craters created by the explosives at a slow speed. No problems were encountered in the first crater, although two or three runs were needed to compact the shale enough for the tank to climb over the lip of the crater. The second crater was negotiated using the same technique with no lateral movements and a low speed. The third crater appeared to be about the same dimension as the first two, but the position of entry of the tank was different. The driver did not approach the crater directly from the rim to the center of the crater and this caused the tank to cant to the right. This caused the right track to work its way off the sprocket. During recovery operations to repair the right track the left track worked its way off the road wheels and broke. After repairs, the tank negotiated the first two craters with relative ease only because the shale was dry. The presence of water or a softer material would have undoubtedly disabled the tank. The fact that the tank driver cannot see into the next crater when he is up on the lip of the preceding crater is likely to make this a common occurrence when craters are placed one behind another as well as in lines perpendicular to the enemy direction of advance.

Appendix D
Crater Comparisons

This appendix contains profiles of the craters analyzed in Chapter 4.

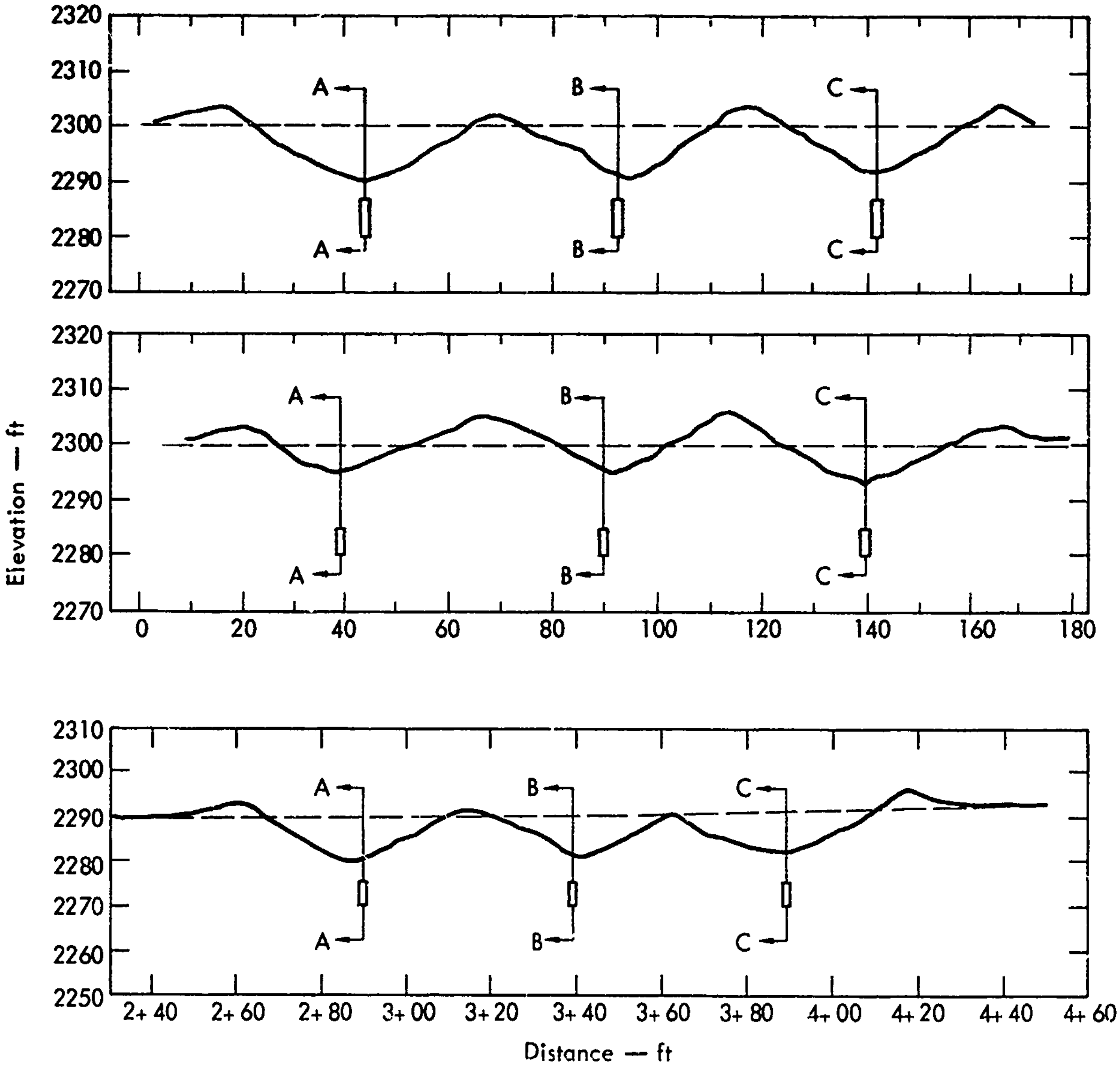

Fig. D1. PC-1, PC-2, and PC-3 longitudinal profiles.

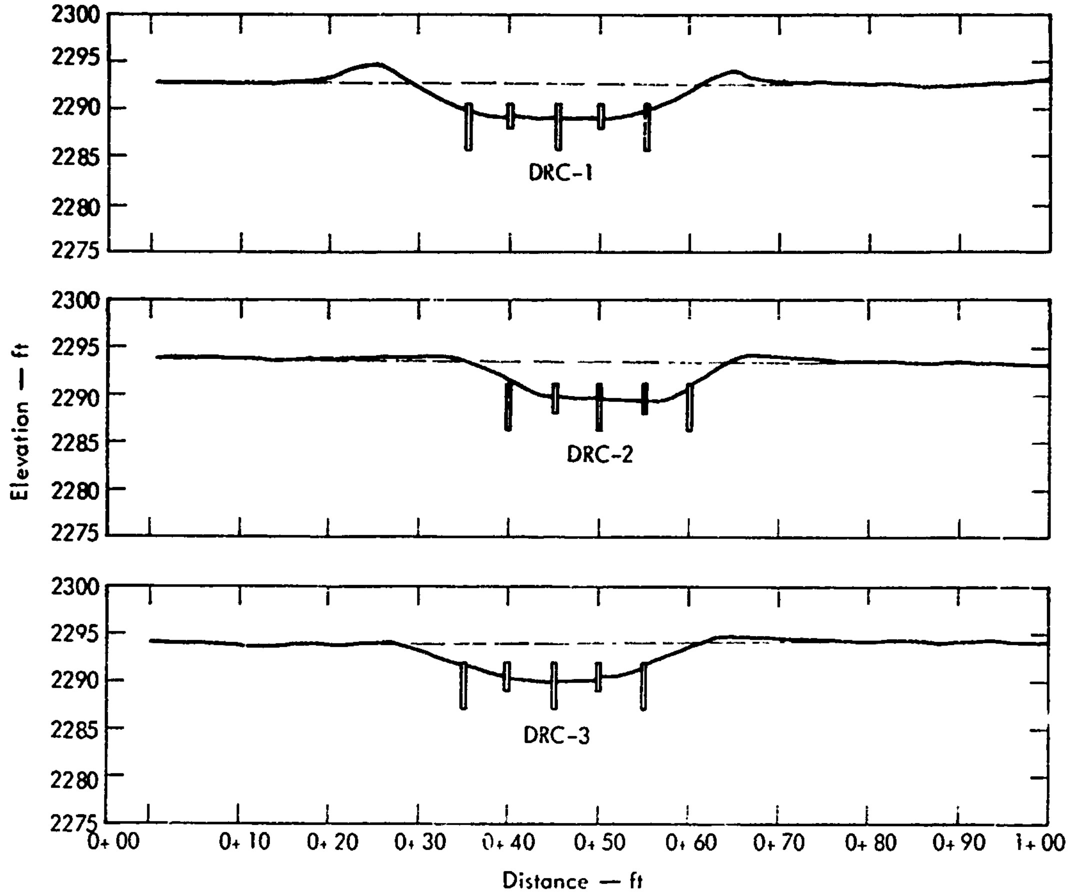

Fig. D2. DRC-1, DRC-2, and DRC-3 longitudinal profiles.

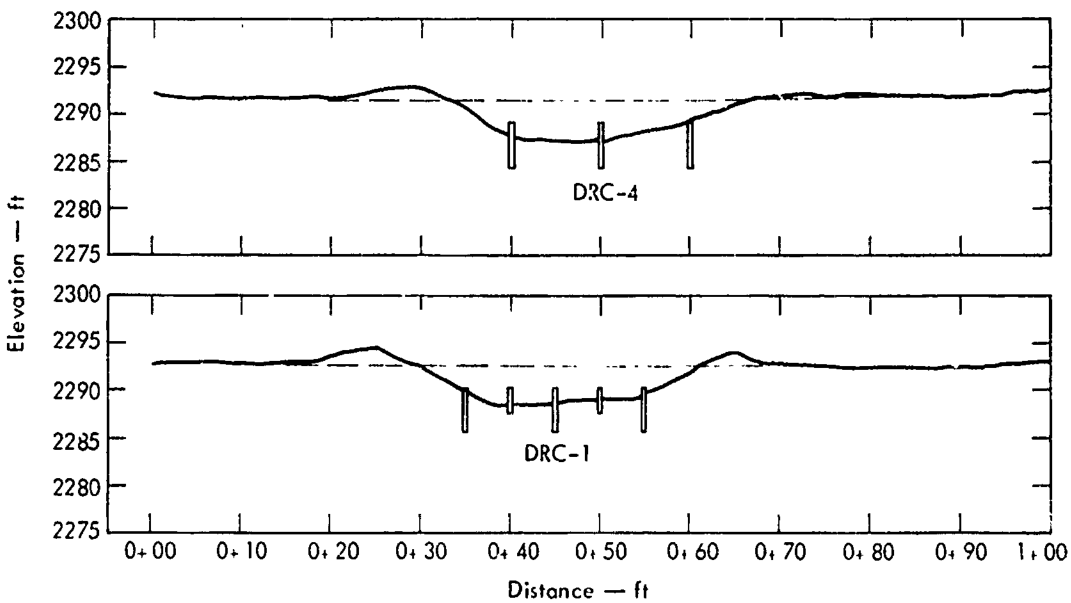

Fig. D3. DRC-4 and DRC-1 longitudinal profiles.

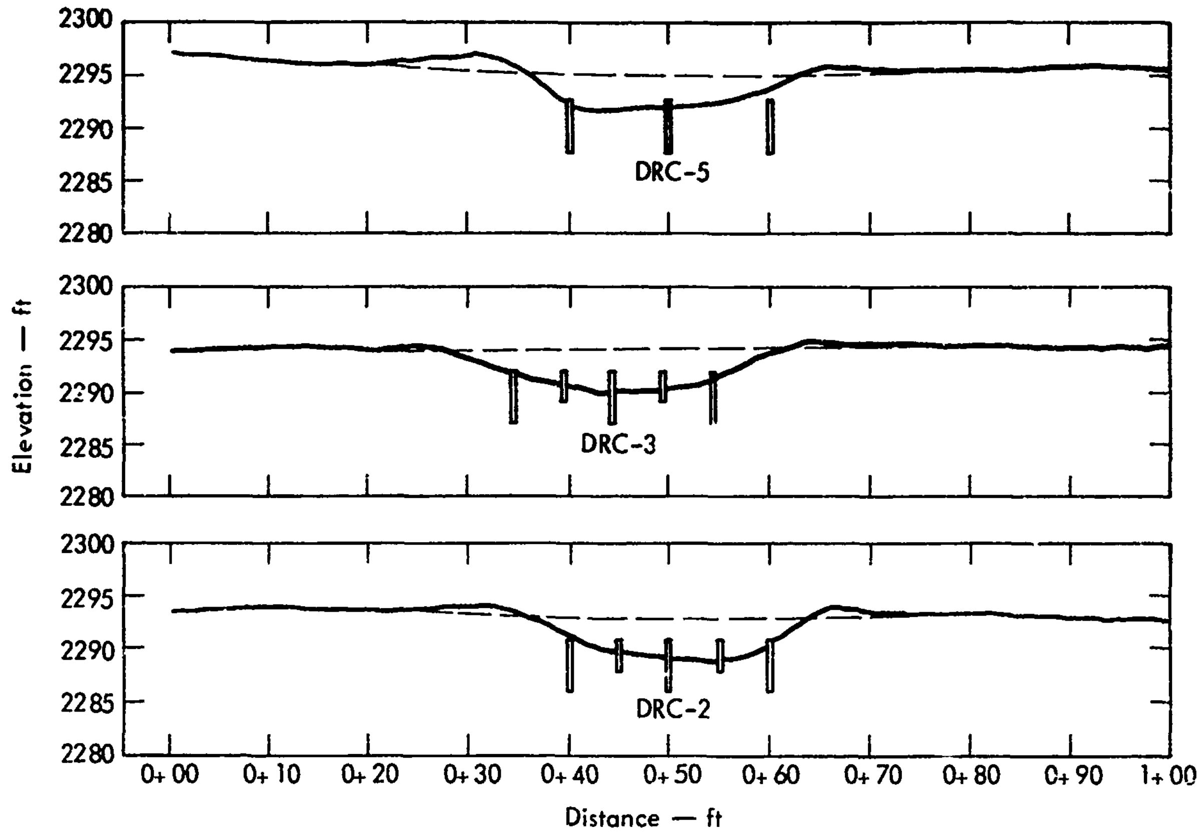

Fig. D4. DRC-5, DRC-3, and DRC-2 longitudinal profiles.

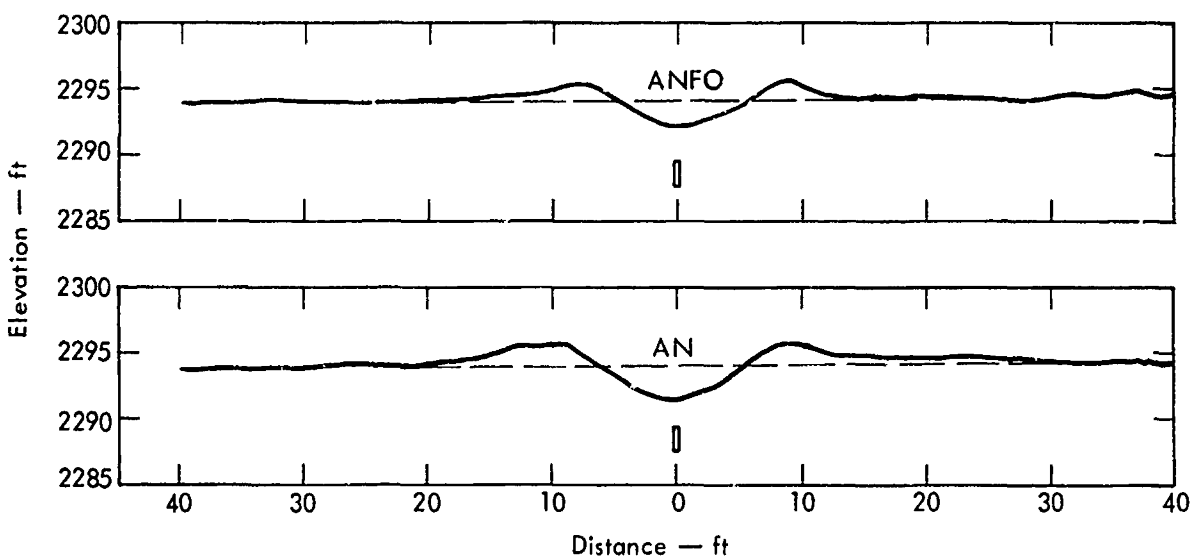

Fig. D5. Ammonium nitrate and ammonium nitrate fuel oil crater cross-sectional profiles.